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Development of a Biohydrometallurgical Process for Leaching Nickel Values from Falconbridge Pyrrhotite Tailings

FINAL REPORT

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Development of a Biohydrometallurgical Process for Leaching Nickel Values from Falconbridge Pyrrhotite Tailings

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Development of a Biohydrometallurgical Process for Leaching Nickel Values from Falconbridge Pyrrhotite Tailings

EXECUTIVE SUMMARY

The objective of this co-funded (DSS-CANMET and Falconbridge Ltd.) study was to evaluate the potential of biotechnology applications to metallurgical processing at Falconbridge Ltd, Falconbridge, Ontario. Following a survey of various Falconbridge environs for process potential microorganisms (Table A), the development of a nickel recovery program from the pyrrhotite-based tailings using autochthonous Thiobacilli was undertaken. Laboratory-scale investigations revealed that Thiobacillus ferrooxidans consistently leaches higher percentages of nickel than a mixed culture containing T. thiooxidans while the presence of catalytic amounts of copper in the bioleach liquor not only caused reduced nickel recoveries but also resulted in lower acid consumption to maintain low pH values (Table B). Pulp densities as high as 20% to 30% had no deleterious effect on the nickel leach values over 21 days but the use of acidic pretreated tailings had no dramatic effects on pH control or nickel leached. Bioconditioning the pyrrhotite tailings before a flotation treatment suggested, through limited testwork, that long bioconditioning times offer little improvement over blank (absence of bacteria) conditioning (Figure A), but also that selective removal of pyrrhotite may be accomplished with a reverse flotation using bioconditioning in an acidic medium. Further work is recommended, to compliment these findings.

Table A

Summary of Types of FBG Microorganisms Isolated and the Applicability to FBG

Types of Organism	FBG Sample Locale	Distinguishing Characteristics	Applicability
Sulphur producer	slag pond marshy sediments	bacterial	Oxidation of sulphide→sulphur (Acid Mine Drainage Control)
Sulphur producer sediments	hard cap marshy bacterial		Oxidation of sulphide→sulphur (Acid Mine Drainage Control)
Sulphate reducing bacteria (SRB)	various	bacterial	Reduction of sulphate→sulphide (Acid Mine Drainage Control)
Heterotroph	various	fungal	metal biosorption
Heterotroph	various	bacterial	tailings pile caps
Thiobacillus ferrooxidans	various	iron oxidizing bacteria	Ni - bioleaching
Thiobacillus thiooxidans	various	sulphur oxidizing bacteria	Ni - bioleaching

Table B

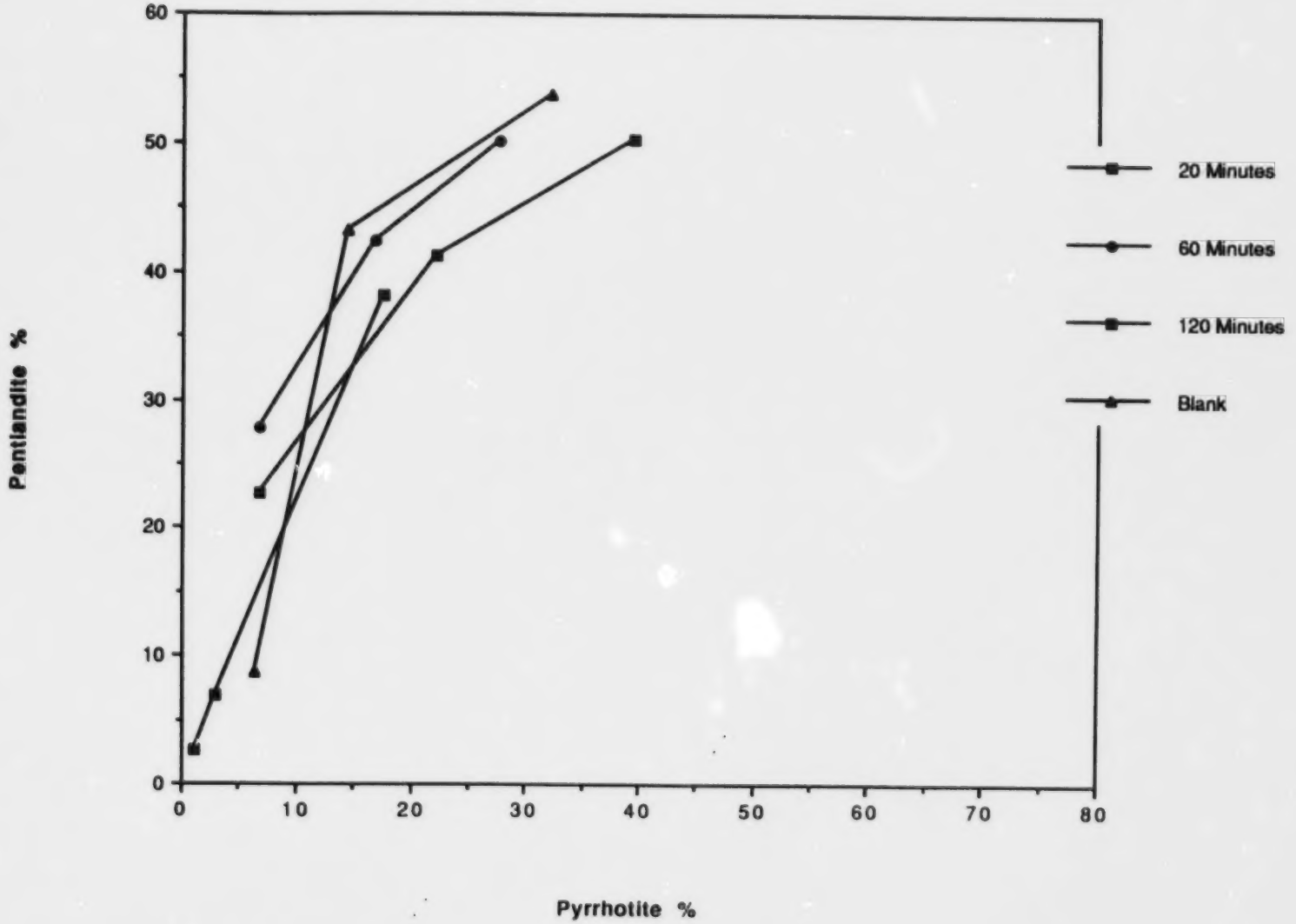
Indications of Physicochemical Conditions on Result Parameters of Bioleaching PO Tails

	Final Average % Ni Extracted	best	Final Average Ni:Fe	best	Average Acid Consumption 12N H_2SO_4/100 g tails	lowest pH	Average Final
Trial 1 (*T. ferrooxidans*)	47.0	51.7	0.188	0.240	1.65	1.61	3.57
Trial 2 (*T. ferrooxidans* and (*T. thiooxidans*)	33.8	45.9	0.022	0.043	1.12	1.05	2.12
Trial 3 (mixed culture)							
with Cu	14.5	20.7	0.018	0.022	1.89	0.72	2.44
without Cu	27.3	58.7	0.018	0.039	1.20	0	1.77
Trial 4 (mixed culture)							
with Cu	31.7	44.8	0.043	0.050	2.90	2.23	2.52
without Cu	25.0	33.3	0.031	0.041	3.37	2.65	2.60

Figure A

Effect of Time of Biopreconditioning on

Pentlandite Vs. Pyrrhotite Recovery by Flotation



1. INTRODUCTION

The production of nickel in the Sudbury area by Falconbridge (FBG) has resulted in much of the surrounding environment being affected and altered in some form by the wastes generated. Among the wastes generated, the pyrrhotite-based tailings are of the greatest volume, with other significant amounts generated by the slag producing operation, and mine water in general. This present program was developed with waste-utilization as a goal and in that respect, the project was developed along two avenues. The first was to survey the FBG environment for bacterial microorganisms capable of being implemented in a further waste-utilization process, and second, the laboratory scale development of a process applicable to the FBG operation.

The direction of the project was monitored by Falconbridge, who provided in-kind support of analytical services, and metallurgical process consultation (Dr. G.W. Heinrich, Co-ordinator), as well as CANMET by providing, as necessary scientific advice and opinion (Dr. R.G.L. McCready). The work was conducted at the Mineral Resources Technology laboratories of ORTECH International, Mississauga, Ontario.

2. EXPERIMENTAL MATERIALS AND METHODS

The experimental work is divided into 3 main tasks with Tasks 2 and 3 overlapping in dimension.

Task 1: Isolation of autochthonous for FBG environs.

Task 2: Biotechnology Bench Scale Development Process and Application.

Task 3: Feasibility Report.

2.1 Isolation of autochthonous bacterial from FBG environs

Both the natural environment used by FBG for waste storage and the mill environment were sampled. Sampling procedures as described in the MEND Field Sampling Manual for Reactive Sulphide Tailings[1] were adhered to for all samples taken. Table 1 describes the sites sampled at FBG. Upon return to the laboratories at ORTECH, appropriate sample volumes were inoculated into various enrichment growth media for initial bacterial isolation attempts.

Sulphate reducing bacteria (SRB) were enriched for by using a lactate-sulphate medium[2]. Upon evidence of sulphate reduction (medium blackening), the Hungate roll tube technique[3] using Starkey's medium[4] was employed for further isolation, in conjunction with an aqueous medium[4] for maintenance of "pure cultures".

Photosynthetic sulphur producers were enriched for in Winogradsky columns[5]. Scrapings of red, yellow or greenish glass side-wall colonies were further inoculated into 60 mL screw top bottles containing Pfennig's medium[6]. These were incubated at room temperature under high light intensity (20 cm from a 30W incandescent bulb). When elemental sulphur was observed on the glass side wall of the bottle, the cultures were subcultured further into the same medium using 10% inoculum. To distinguish between algal and bacterial growth, 10 mg $CuSO_4.5H_2O$ per litre medium was used as an inhibitor of algal growth[7].

Iron-depositing bacteria of the Gallionella genus, were enriched for using an iron sulphide medium[8] with observations based on the characteristic twisted ribbon-like tail morphology of colony formation[9].

Aerobic heterotrophic bacteria were enriched for using both neutral and acidic forms of organic media. Aqueous samples were inoculated onto solid agar plates[10] prepared with Malt Extract (ME) Agar, Sabouraud Dextrose (SA) Agar, Nutrient Agar (NA) and Tryptone Glucose Yeast Extract Agar (TGE) all from Oxoid. Acidic forms of organic medium[11] were inoculated in a similar fashion but employed both solid and aqueous preparations of citric acid (1M and 0.1M) and malic acid (1M and 0.1M) in an inorganic salts broth [in g/L $(NH_4)_2SO_4$, 0.15; KCl, 0.15; K_2HPO_4, 0.15; $MgSO_4.7H_2O$, 3.36; $CaCl_2$, 0.97; $Al_2(SO_4)_3.18H_2O$, 2.25; $MnSO_4.H_2O$, 0.12]. Significant growth of microorganisms on agar plates was recorded as positive only if the colony counts were between 30 and 300. Positive growth in aqueous media was observed only if the medium became turbid. Media was heat sterilized at 121°C for 15 minutes. Acidification of media was with sterile 12N H_2SO_4 (to pH 3). Agar suspensions of the citric and malic acid preparations were made with 1% Oxoid agar, the agar suspension being acidified at 40°-50°C following sterilization, and combined aseptically to produce complete culture media. Plates were incubated inverted, under glass or plastic (to conserve moisture) for up to 28-35 days at room temperature. Successful colony isolations were subcultured to pure culture form and noted for extracellular polysaccharide production, cellular morphology under 100X oil immersion microscopy, and tested for the Gram stain reaction.

Enrichment for Thiobacillus ferrooxidans (T.f.) and Thiobacillus thiooxidans (T.t.) proceeded using ferrous iron [33.3 g $FeSO_4.7H_2O$/L) and sulphur [50 g/L] based media, respectively(12). Ten percent (v/v) inoculations were made from various FBG samples with the successful T. ferrooxidans enrichments being subcultured 3-4 more times before being inoculated [10% (v/v)] into pyrrhotite tailings containing (5% and 10% w/v) M9K (minus $FeSO_4$) medium. The T.t. cultures isolated were subcultured into Starkey's medium with 50g sulphur/L medium sprinkled on the surface but not adapted to the tailings. The T. thiooxidans cultures were checked for the ability to oxidize iron. All 3 strains were subcultured into M9K plus ferrous iron, incubated at room temperature for 28-35 days without any evidence of iron oxidation greater than that of the control without inoculum.

The analytical chemistry department of the Metallurgical Technology Centre, Falconbridge Ltd., made the necessary analyses of all the aqueous and solids samples generated in this project. Solids were analyzed for Ni, Fe, Cu, S (as necessary) using bromine-acid digestion by Inductively Coupled Plasma (ICP). Aqueous samples were analyzed using nitric acid and ICP.

2.2. Biotechnology Bench Scale Development and 2.3 Process Application

Following the isolation of several bacterial cultures, a meeting held between FBG and ORTECH on December 12, 1990 determined that biotechnology bench scale developments should proceed with attempts to bioleach nickel from the PO tails provided by FBG.

Interest was also present for using Thiobacillus ferrooxidans as a surface modifying agent in an attempt to suppress or float the pyrrhotite or pentlandite fractions of the PO tails.

Nickel leaching on a laboratory scale was initiated using all seven T. ferrooxidans strains isolated from the FBG environment, as well as one copper leaching strain courtesy of Dr. I. Suzuki, University of Manitoba. The first trial (Trial 1) was conducted to observe the effect of T. ferrooxidans only. Tests were conducted using the following parameters: total bioleach volume 200 mL in a 500 mL Erlenmeyer flasks, 80-85% M9K salts [per L: $(NH_4)_2SO_4$, 0.4 g; K_2HPO_4, 0.1 g; $MgSO_4.7H_2O$, 0.4 g], 10% inoculum (PO tailings adapted T.f. slurried suspension) 7-7.5% tailings pulp density (p.d.), room temperature, 200 rpm agitation on a gyrotary platform shaker. Daily additions of 12N H_2SO_4 were added to adjust the pH during the first 3 days and on the sixth day, and then allowed to assume a natural course. Control experiments were run concurrently, the inoculum being replaced by 10 mL of a 2% (w/v) thymol in methanol solution. Slurried samples were withdrawn, aseptically, on days 0, 1, 2, 6, 14 and 28, frozen to kill the Thiobacilli, then thawed and filtered through Whatman #1 filter paper for further analysis by FBG for Ni and Fe.

Thiobacillus thiooxidans (0-9) was incorporated into experiments conducted in a similar fashion as the T.f.-alone tests. Methodology differences were: for Trial 2, the tests were done in 100mL volumes in 250 mL Erlenmeyer flasks with 10% (v/v) each of T.f. and T.t. inoculum; pulp densities were between 9% and 10%; for Trial 3, each of three different T. ferrooxidans cultures (SM-4, 0-3, fecunis) were used in combination with the 0-9 T. thiooxidans; 60 ppm or 120 ppm Cu (as $CuSO_4.5H_2O$) was added to the medium,

pulp densities as low as 3.6% were used in 50 mL and 100 mL volumes in 250 mL Enlenmeyer flasks shaken at 250 rpm, the pH was monitored and adjusted more often during the 21 day leach; for Trial 4, the inoculum consisted of 5 mL each of the fecunis and the 0-3 T.f. with T.t. cultures from Trial 2 plus 7.5 mL (0-9) T.t., the pulp density was increased to 20%-30% in 100 mL volumes in 500 mL Enlenmeyer flasks at 250 rpm gyrotary shaking and pH monitoring and adjusting as for Trial 3.

Moisture determinations were made in duplicate or triplicate on representative samples of unleached tailings. A thinly smeared 3 - 10g sample of tailings was oven dried at 105°C for 1 hour, weighed, redried again for 1 hour then allowed to acclimate to atmospheric moisture conditions. An average was then calculated.

Preconditioning of the tailings with a 1N H_2SO_4 treatment was used in Trials 3 and 4. Although a number of methods were attempted the one finally used was the following: 30-50 g wet weight PO tails contacted with 100 mL 1N H_2SO_4 for 3 hours, decant and filter through Whatman #1 filter paper, then use directly in the leaching tests.

Results of bioleach Ni and Fe analyses were calculated as following: Solids, reported as Ni and Fe in ppm concentrations, were converted to the value corresponding to the pulp density (eg. dried tails sample ppm x pulp density). The leach solutions analyzed by FBG and reported in ppm, were subsequently converted to percent Ni extracted from the original sample (eg. aqueous Ni ppm ÷ original sample ppm).

The sample Fe reported in ppm was calculated as a Ni:Fe ratio to three decimal places. The 3-digit significant value was based on the calculation of low Ni concentrations (≤500 ppm) divided by high Fe concentrations (≤20,000 ppm). Calculated results were plotted as time (x-axis) vs % Ni leached, Ni:Fe and pH all on the y-axis.

Tests to investigate the biological surface modification of the pyrrhotite or pentlandite fractions of the tails were conducted to determine the applicability of using Thiobacillus in a flotation process.

Methodologies were adapted from a patented process[13] whereby the adsorption on to a mineral surface by T. ferrooxidans will cause the depression of that mineral species during a flotation process. To obtain large numbers of T. ferrooxidans, 30L and 50L volumes of unsterilized M9K medium with ferrous iron were inoculated (5-10% v/v) and incubated at room temperature in a 60L (65cm x 35 cm) batch growth plastic tub. Upon termination of growth, ferric iron was initially removed by settling and decantation, the resulting aqueous passed through the Millipore ultrafiltration Pellicon system, using a 0.2 µm GVLP filtration cassette. The original 30L and 50L volumes, now reduced to 400 mL, was centrifuged at 100-200 rpm, 10 minutes, to remove ferric iron and then at 10,000-12,000 rpm to pelletize the cells. The cells were washed twice (50 mL per) in M9K salts solution and further diluted to a count of 2.5×10^9 cells per mL (50 mL total volume) using the Improved Neubauer Levy-Hausser corpuscle counting chamber under phase-contrast microscopy.

Work-up for the flotation procedure consisted of feed preparation as follows: Filter as-received PO tails pulp (~12.5 kg) through a Booth filter press to a filter cake of 6.4 kg. Apportion the filter cake into 510-515 g batches and store in double plastic bags frozen. Grinding the above batches was done in a laboratory scale rod mill (19 cm dia. x 25 cm) using 10 kg steel rods, 0.3 kg H_2O for 35 minutes. The rod mill was discharged by washing with excess water into a bucket, the pulp settled for 15 minutes and the excess water decanted, then transferred to the Denver 1L float cell. Total elapsed time from the rod mill to the float cell of 21-23 minutes.

Float cell parameters were 40% solids pulp density, mixed at 1500 rpm with air injected at 1L/min. Flotation reagents added were (per 450 g dry wt. solids): Sodium isobutylxanthate (SIBX) [25 g/t] and Dowfroth 250 [5 g/t] for 2 minutes. Froth was collected using 20 skimming strokes per minute for 1 minute, 2 minutes and 7 minutes. Froth products and tails were pressure filtered (Booth) oven-dried at 80°C, and weighed for percent recoveries. *T. ferrooxidans* (0-9) was added to the flotation at the start for 20 minutes, 60 minutes and 120 minutes tests. The natural pH of the mixture was not adjusted, except for Test 6 whereby H_2SO_4 was used to reduce the pH.

3. RESULTS AND DISCUSSION

3.1 Isolation of Autochthonous Bacteria

Lactate-sulphate medium inoculated with FBG environment samples originating from marsh, hard cap and tailings sediment resulted in a number of positive blackened aqueous conditions (Table 2). Black sediment mud from the old tails area, conservation area sediment mud, slag pile marsh sediment, and sediment from the old tails area (Figure 1) all produced isolations of the sulphate-reducing bacteria (SRB). The inoculation of the positive flasks into Hungate roll tubes resulted in the further ability to isolate single colonies. By repeating the cycle of inoculation into the Hungate then into the maintenance medium of a single black dot colony, 10-15 unverified, unidentified "pure" cultures of SRB have been isolated. These are being occasionally subcultured and maintained for any further interest by FBG.

Marshy sediment well below the surface was the type of locale associated with SRB isolation. Because SRB's are obligately anaerobic and thrive in an environment with plenty of organic matter this is not unexpected. The tailings areas and mine water pond sediment may be poor in both conditions, therefore SRB's were not isolated. SRB's do hold a great amount of potential in any sulphate neutralization program in conjunction with the requisite developmental stages taken. With the increased profile of the deleterious effects of acid mine drainage and metal mobilization due to sulphate production, an SRB population isolated from the FBG environment could serve a key role. While there are a number of processes in operation[14, 15] using both sulphur producers and SRB's, one[16] operation utilizers field-adapted SRB's alone.

Sulphur-producing photosynthetic bacteria were isolated from both a slag pond marsh sediment and from the hard cap area marsh sediments (Figure 1). Both bacterial isolates originated from Winogradsky column scrapings which showed a red tinge at the glass-mud interface. Of seven different FBG solid sediment samples inoculated into 7 Winogradsky columns, five failed to yield any evidence of bacterial cultures. These were (Figure 3):

(T-2) 1. Hardy lake tails sediment.
(H-1) 2. Hard cap with visible sulphur deposits on the surface.
(S-5) 3. Conservation area sediment with detritus.
(0-11) 4. Onaping mine pond water sediment.
(S-4) 5. Marsh sediment near slag pile.

A number of glass-mud interface scrapings did produce sulphur upon subcultured into the Pfennig's medium but these were determined as being algal in nature due to inhibition of growth in the presence of copper. Because the Winogradsky columns were exposed to daylight instead of incandescent light, it is probable that algae were selected for over bacteria. Incandescent light was used for the further enrichment in Pfennig's medium, however, algal cultures had already been selected for in the columns, therefore excluding maximum bacterial colony development. No further work resulted from the isolation of these sulphur producers, so the bacterial cultures were stored at 4°C in Pfennig's medium as grown. The utilization of biologically-produced sulphur does have applicability in sulphate waste streams[14, 15] and would require more detailed research to develop.

All of the FBG samples obtained (Figure 1 to 3) were inoculated onto/into organic carbon containing media in an attempt to isolate heterotrophic bacteria. Table 3 summarizes the morphology, motility, gram stain reaction, type of medium isolated on, presence of excess polysaccharide production, and sample site of isolation. Low numbers of bacterial colonies grew on/in a large number of the media but only those presenting growth in colony formation >30, <300 were taken as significant. A variety of fungi were isolated from the environment (data not shown) but were not considered to have significant potential in application to this project. Only two significant counts of acidophilic heterotrophics were isolated, that being from the Moose Lake Treatment Plant area (Table 3), both gram positive, non-motile and not great producers of extracellular polysaccharide. Not a great amount of potential is viewed within these findings. Considerably more bacteria and/or yeast were isolated from neutral pH organic media. Most of the isolates were rods and non-motile, although motile spheres and rods were observed. Extracellular polysaccharide production was noted in 4 isolates, 2 of them being bacterial and 2 of them probably yeast.

The presence of neutral pH heterotrophic organisms within the processing circuit at the Strathcona mill may reflect the use of various organic conditioners and reagents in use during these processes.

Slime producers isolated from the low pH (3.5) waters of Cranberry Lake as well as the discharges from Strathcona mill and Fraser yard could play a role in an as-yet untested application. Although no testwork was undertaken with these microorganisms, the environment they were isolated from indicates potential for tailings applications, whether in a containment or a control mode. More in-depth characterizations, isolations and testwork would prove any further potential for an application in the mitigation of Acid Mine Drainage.

Iron-depositing bacteria, Gallionella, were expected to be found in the iron-rich environment of the slag pile run-off water, however this was not the case. Microscopic examination of enrichment cultures revealed none of the characteristic Gallionella morphology of twisted ribbon tails. The results do not necessarily mean an absence of these types of bacteria, but, that if they would be required for a process applicable to FBG, that a more extensive sampling and isolation procedure would be needed.

The isolation of a seven different T. ferrooxidans and 3 different T. thiooxidans allowed for an extensive investigation of the effect of these strains on the leaching of nickel from pyrrhotite tailings material. Of the 7 T. ferrooxidans strains, all were isolated from the outdoor FBG environment (Table 4), (Figure 2, 3), while the T. thiooxidans were isolated from the mill (2 strains) and the environment (one). Indications of successful isolations were, for T. f., a colour change of the M9K medium from ferrous green to ferric red-brown much faster than the control flask while the T. t. caused the turbidity to increase and the pH to decrease to low levels in sulphur-containing media (Table 5). The T. f. strains were then subcultured into an aqueous tailings (10%) environment where they became acclimated to PO tails.

Although the pH behavior of the control flask (Table 4) was similar to the I. f. flasks, the difference was the ultimate colour changes, the control flask staying a relative grey colour; the I. f. flasks assuming a reddish-brown colour due to the ferrous to ferric iron production.

3.2 Biotechnology Bench Scale Development and Process Application.

Testwork now proceeded from the isolation of suitable organisms, to the development of processes applicable to the Falconbridge environment. Following meetings with FBG personnel, it was concluded that research should be undertaken to investigate the applications that the isolated Thiobacilli may have on the tailings, as produced by Falconbridge. Development progressed in the way of initially, scoping tests to determine optimal strains of Thiobacilli to use, then progressed by trying to increase the kinetics of nickel leaching as well as the percent Ni leached from the original tails sample. Finally, in an unrelated series of tests, the effect that a strain of tails-adapted I. ferrooxidans has on the flotation characteristics of PO tails was studied.

The first bioleaching tests were done with each of 8 different strains of isolated I. ferrooxidans, and are exemplified by Figures 4, 5 and 6 and Table 14. There is a maximum percent nickel release during the first 1-2 days which is 3-6 times that of the rate per day over 14 days while Per Day Rates of % nickel extracted decrease continually to 28 days. Sterile control values are lower than the bioleach tests and generally leach about half as much nickel over 14 and 28 day periods (Table 6). Acid consumption was similar in all tests performed (including control) with final pH values stabilizing at approximately pH 3.70.

Iron values (Fe) were calculated compared to Ni values and by the end of the bioleach are greater and generally about twice that of the sterile control. The Ni:Fe ratio increases in these tests from an as-received value in the tailings of about 0.017 to values that by day 28 have increased to 0.130 and approximately 0.210 in the control and bioleach test aqueous, respectively (Table 7 and 14). Red-brown leach liquor colour was noted in all the tests, with the sterile control assuming the colour slower.

Further tests conducted using a combination of each of the above T. ferrooxidans and one strain of T. thiooxidans (0-9) had significantly different results (Tables 8, 9, 14 and Figures 7, 8, 9, 10). The major difference noted was the percent nickel extracted. Maximum percent Ni extracted was less than the T. ferrooxidans tests as was the rate per day over 14 days and 28 days. Six of the eight mixed cultures tested had at total of <30% nickel leached while the sterile control had 16.4%. The bioleaching rates when taken in context to the control tests of each trial were comparatively greater in the T. ferrooxidans trials than in the mixed trials, although two mixed cultures (Fecunis, 0-9) displayed as good or better. Acid consumption was less in the mixed culture trials as was the final pH values. Final pH values of less than pH 2 to 2.1 displayed a yellowish colour to the leach liquor, while those pH values greater than pH 2.25 had a red-brown coloration. One notable exception was the grey black colour, final pH 2.32, of the SM-4 mixed culture test. Iron values in solution were considerably less at day 14 and day 28 in the mixed cultures (Table 9), the ultimate result being one whereby the iron remained in solution at a higher concentration or alternatively, was more easily extracted from the tails.

Three mixed culture T. ferrooxidans were selected for further testwork designed to examine the effect of copper in solution as a catalyst, and the effect of a lower pulp density on the leaching kinetics (Trial 3 - Tables 9, 10 15, 17 and Figures 11 to 17). Combined with freshly sulphur-subcultured T. thiooxidans (0-9), the three T. ferrooxidans (Fecunis, 0-3, SM-4) mixed cultures showed that apart from 2 tests (0-3 low pd - Figure 13 and Fecunis 100 low pd - Figure 16), the rates and the total Ni leached were lower than the T. ferrooxidans trial 1 tests (Table 10). Two concentrations of copper were tested; 60 ppm and 120 ppm in pulp densities between 7-12%. While the sterile controls had 2.7% Ni extracted into each (60 and 120 ppm Cu) the bioleach tests never exceeded 21% in 21 days (Figures 11 and 12). Ni:Fe ratios were invariably low, showing an increasing trend up to Day 6 or Day 14, then decreasing (Table 11). In one test (Fecunis 100), untreated ore (compared to pretreated acidified ore) was used with 60 ppm Cu in solution but presented indifferent results.

The sterile controls required only one minor acid adjustment for pH regulation (<3) in the presence of the soluble copper, while, although more acid was required for the bioleach tests, no conclusive trends were established between the two copper concentrations (Table 15). Considerably less acid, however, was required where more aeration was present; ie. all copper tests except fecunis/T.f. 100 mL copper inclusion tests. Less aeration, as in the 100 mL vs 50 mL total volume, resulted in 3-4 times as much acid consumed to attain pH <3. The exclusion of copper from the medium did allow for increased nickel extraction values into the sterile controls (15%) as well as in the bioleach tests, (Tables 10 and 15).

Although 60% nickel was leached by the 0-3 mixed culture using a 5.2% pulp density, the rest of the tests using a low pulp density (5-9%) or moderate (8-11%) p.d. did not exceed 27% nickel extracted, however one test using 3.6% p.d. untreated ore did attain 35.6% nickel extracted. Except for the sterile controls, a more consistently low pH (<2.1) was attained by day 21 without acid additions after day 14. With the exclusion of copper, the sterile controls required more than 15 limes the amount of acid and finished with a final pH >4. Ni:Fe ratios were invariable close to the original sample ratio through the above tests, and only increased slightly with the 60% Ni leached in the 0-3 example given. Increasing the aeration had relatively no effect. The leach liquor colour was generally an orange-grey tone, the one exception being the test with 58% Ni extraction being a red-brown colour.

Trial 4, using mixed culture T. ferrooxidans and T. thiooxidans, examined the effect of high pulp density on the nickel leaching characteristics of untreated vs. acid treated ore, with and without copper (60 ppm) in solution (Tables 12, 13, 16, 17 and Figures 18 to 21). Higher pulp densities (20-30%) of these PO tails resulted in generally greater bioleached nickel values, higher Ni:Fe ratios and increased acid consumption. The lowest percent nickel bioleached was associated with the acid-pretreated ore where the 30% (approximately) p.d. with and without copper tests and the 21% p.d. without copper test (Figure 19) all leached (approximately) 20% nickel. This is compared to the sterile control value using untreated ore (30% p.d.) which leached 15.5% nickel (Figure 19).

The acid pretreated ore had, with one exception, (20% p.d. with copper) the lowest rates of nickel extraction per day at 14 days and 28 days, however, the initial maximum percent nickel extracted within the first 48 hours was 6.1% and 5.5% without copper present (20 and 30% p.d., respectively) while the presence of copper caused the lowest rates at 3.3% and 2.9% in 20 and 30% p.d., respectively (Table 16). This is compared to the highest maximal 48 hr. rate of 8.3% nickel leached in untreated ore at 30% p.d. and the sterile control value of 4.5%.

Acid consumption was lowest when copper was present with acid pretreated 20% and 30% pulp densities, as well as 30% p.d. without copper, and relatively similar in acid consumption for the rest of the tests. The test using untreated ore with copper present showed exceptionally good leaching characteristics (Table 16, Figure 18), at 44% nickel extracted and relatively high rates per day at 14 and 28 days. Nickel to iron ratios were seen to be increased over the results from Trial 3 but not as significant as those from Trial 1, T. ferrooxidans only (Table 13). Final leach liquor colour was generally a light orange colour, with one test (acidified ore 20% p.d.) remaining a colorless grey. These light colours are similar to those found in Trial 3 but different from Trials 1 or 2.

The consistency of higher percentage of nickel leached involving I. ferrooxidans and those mixed cultures in which it appears to predominate appears throughout the study. Of the tests performed in Trial 1, the amount of bioleached nickel never fell below 43%. In the mixed culture trials where an orange-red-brown colour predominated, the nickel values were tending to be of the higher percentages. This is in contrast to those lighter-colored mixed culture trials which usually attained 30% or less nickel leached. Predominance of one culture over another within a mixed culture has been noted by Suzuki[12] who also found that the mixed cultures were not significantly better at leaching in shake flask studies but also that the presence of I. thiooxidans enhanced Cu leaching from a sulphide ore when conducted in columns. The fact that nickel is being leached at a higher rate using I. ferrooxidans suggests the importance of ferric iron in this process. Ferric iron has been implicated in the "direct" leaching of sulphide minerals[17] where it may double metal extraction rates. "Indirect" leaching is probably also playing an important role[17] with the ferric sulphate acting as a strong oxidant in the dissolution of nickel. The role of ferric iron in bacterial nickel leaching has also been detailed by Dutrizac and McDonald[18] whereby bacterially generated ferric iron was consumed by the pentlandite ore in terms of a chemical reaction. Nickel recoveries were also shown to be controlled by the availability of ferric species in solution due to the bacterial oxidation of pyrrhotite and pentlandite[19] in low grade nickel material.

The control of pH during this work has appeared to have similar consequences as above in that low pH values (<2) have resulted in poor nickel recoveries. In contrast, where the pH stabilized at greater than 2.5 to 3 and where T. ferrooxidans was the primary strain, the nickel recoveries were significantly increased. The predominance of T. ferrooxidans in mineral sulphide leaching may, through the organisms effect on pH in the system, contribute to the observed higher nickel recoveries. Duncan and Trussel[20] have speculated that at pH values exceeding 3, ferric hydroxide precipitates, sulphuric acid is produced, thus lowering the pH, and maintaining a strong mineral sulphide oxidizing environment of ferric sulphate in solution. High acid strengths have been implicated in the suppression of nickel dissolution[18] during pentlandite bacterial leaching, a situation not unlike the present study.

It was originally hypothesized that the presence of small amounts of copper in the leaching medium would catalyze the nickel solubilization in much the same manner that silver ion catalyzed copper dissolution from chalcopyrite[21,22]. Falconbridge consultants suggested copper be used instead of silver due to its proximity to silver in nobility, its availability, and its economy. The presence of copper in the medium did result in reduced nickel recoveries both in the sterile control and bioleach tests and, with exception, decreased acid consumptions and/or lower final pH values. The reduction in nickel recovery is not assumed to be due to copper inhibition as many reports have dealt with the high tolerance of Thiobacilli to copper[23,24]. In the sterile controls, the presence of copper facilitated a low final pH (<3), very small acid additions, and very low nickel and iron concentrations.

Assuming that there is a relative initial absence of ferric iron as leaching agent in the sterile controls, without the presence of bacteria to regenerate the ferric iron supply the resulting nickel and iron concentrations would be as stated, low. Without the ferric iron to contribute to an increasing pH[20], the pH would remain stable at a lower value. Additionally, ferric iron as an oxidant will preferentially interact with the copper constituents (chalcopyrite) in the ore[25]. Although the solution Eh nor the electromotive force of the metal bearing minerals was determined and that these factors play a role in any chemical or biochemical process, the possibility does exist that the presence of copper as a potential catalyst in the medium caused a preferential shift in chemical reactions towards the cupric-cuprous-ferric-ferrous equilibrium.

Testwork on the selective flotation of the different metal/mineral constituents of the pyrrhotite tailings was conducted by subjecting the process to 3 different times of bioconditioning, to a pH change and to a higher frother dose, with appropriate blank tests. Results are presented in Tables 18-26 and Figures 22-36. Initial grades of the as-received material was: 0.7% Ni, 0.05% Cu, 30-32% S, 0.57% pentlandite, 0.15% chalcopyrite, 75% pyrrhotite. Pentlandite and chalcopyrite displayed the same characteristics as reported below for nickel and copper in slightly different percentages.

Baseline Blank Tests (Tables 18 and 19)

Based on 20 minute blank conditioning, the grades of Ni, Cu and S increased to the third concentrate collected (2.93%, 1.97%, 23.5%, respectively) and was accompanied by low Ni recoveries (<12%), higher Cu recoveries (29%) and low S recoveries (<3%).

High Frother Dose (Table 20)

Nickel grade and recovery was highest in the first concentrate (2.66%/17%, respectively) while Cu grade and recovery was highest in the third concentrate (1.08%/29%). Sulphur showed stable grades throughout (30%) with a maximum of 9% recovery in the third concentrate.

Regular Frother Dose (Table 21)

No major changes in grade were reported for nickel (2.50%) between the three concentrates while the highest recovery was in the third concentrate (25%). For copper, the highest grade reported to the second concentrate (1.07%); the highest recovery in the third concentrate (47%). Sulphur showed stable grades (30%) throughout, low recoveries in the first and second concentrates (1%) and 15% recovery in the third.

Acidic Bioconditioning (Table 23)

Low, stable nickel grades (maximum 1.29%, first) with similar low recoveries (11-15%) while Cu achieved higher grades and recoveries in the first concentrate (0.74%/37%). Sulphur had stable grades of 32% with similar recoveries of 17-22%.

60 Minutes Bioconditioning (Table 22)

Nickel had the highest grade and recovery of this test and of all the bioconditioning tests in the first concentrate (4.17%/21%), while steadily decreasing to the third concentrate (1.26%/8%). Copper showed the same trend (2.21%/50%) in the first to third concentrates (0.29/3%) while sulphur had all concentrates reporting about 31% grades with low recoveries (7-10%).

120 Minutes Bioconditioning (Table 24)

The nickel grade and recovery was highest in the first concentrate (3.80%/17%) and decreased to the third (1.12%/11%) as did Cu (2.06%/44%); (0.22%/10%) while sulphur was stable with a grade of 32% and 7-16% recoveries.

120 Minutes Blank Test (Table 25)

The highest grade and recoveries were in the second concentrates for Ni (4.53%/26%) and Cu (2.80%/65%) while S exhibited stable grades (31%) with increasing recoveries (7-16%).

Table 26 details additional information gathered during the actual flotation. The natural pH of the complete mixture without the bacteria was pH 8.0-8.8. When the Thiobaccillus bacteria were added, the pH decreased to a minimum of pH 7.5-7.7. Acidic conditioning before addition of the bacteria decreased the pH to 4.0, and then to pH 4.8 after 5 minutes and the addition of the bacteria, and the reagents. A voluminous float was observed with the acidic treatment.

Effect of Bioconditioning on Nickel Flotation Products

Using the natural pH of the complete flotation mixture allows for higher grades than and similar recoveries as the acidic flotation mixture (Figure 28). Figures 22, 25 and 28 show that 60 minutes of bioconditioning provides the highest grade and that a high grade is restricted to about 35% recovery at which point the grade begins to fall off (blank, 120 minutes).

Effect of Bioconditioning on Cu Flotation Products

A significantly increased grade of copper was observed in all the flotation products with the recoveries increasing with each successive concentrate collected. Cu recoveries increase with 60 minutes and 120 minutes bioconditioning compared to 20 minutes (Figures 26, 32) while the blank conditioning of 120 minutes gave similar grades and recoveries as 60 minutes bioconditioning. The pH did not affect the results in the same manner as it did nickel (Figure 29).

Effect of Bioconditioning on Pentlandite Vs. Pyrrhotite Recoveries

As it was for nickel recoveries, natural pH increases the pentlandite recoveries (38%) while the same time limiting pyrrhotite recoveries (17%) (Figure 30). The acidic pH drives up the pyrrhotite recoveries. Pentlandite recoveries were highest (27%) in the first concentrate at 60 minutes bioconditioning while limiting pyrrhotite (7%) (Figure 27) recoveries.

During the longer bioconditioning time of 120 minutes, the blank had slightly better results collected in the second concentrate but the same as 60 minutes bioconditioning for the second concentrate collected (Figures 27, 33).

Effect of Frother Dose on Recoveries from Bioconditioning

The increased frother dose seemed to increase the recovery of nickel while maintaining relatively similar grades (Figure 34). The copper grade was decreased with a higher frother dose (Figure 35). Figure 36 shows that increased pentlandite and pyrrhotite recoveries are made with the higher frother dose, although percentages of pyrrhotite are kept below 25% while pentlandite ranges from 21% to 40%.

The results of this limited initial investigation on the effects of bioconditioning on flotation products recovered suggest the need for a more in-depth undertaking. However, certain trends do emerge. Most notable is that from a higher pentlandite vs. pyrrhotite recovery, the 120 minutes blank conditioning was as good as or superior to the results obtained from 20, 60 or 120 minutes bioconditioning. One hour of bioconditioning was described by the McCready et al patent[13] as being an optimal contact time, as the 60 minutes contact time here was optimal as well. Long conditioning times appear to enhance the flotation selectivity of both the nickel and copper mineralization. The test results show that flotation selectivity (less pyrrhotite floated) diminishes after about 35% of the nickel mineralization has been floated, thereby indicating that the remaining mineralization is not liberated.

The fact that pyrrhotite is floated in favour of Cu or Ni mineralization in an acidic mixture suggests that, in combination with bioconditioning, an acidic medium is conducive to pyrrhotite recovery. An alkaline medium has been shown to decrease sulphide flotation after bioconditioning[26], and as such the concept of reverse flotation to exclude pentlandite may be considered.

The incomplete study of this bioconditioning phenomenon suggest a number of investigations to follow-up with. Because of a low degree of pentlandite liberation, an extended regrind of the tails may prove advantageous. The reagent balance may indeed require alteration due to the effects of bioconditioning. The effect of the strain of T. ferrooxidans used may cause variability in that the difference in the rate of sulphide mineral oxidation predetermined its effect on the flotation properties[26]. This fact, plus the option of using a recycle stream from a growing population of sulphide mineral oxidizers[13], may both contribute to the potential of using this application of biotechnology at Falconbridge.

4. CONCLUSIONS

The testwork conducted by ORTECH International for the Department of Supply and Services and CANMET in conjunction with Falconbridge Ltd. has concluded the first phase of the examination of biotechnological investigations applicable to the mine environment of Falconbridge. The focus of the study became the application of biotechnology to the utilization of the massive amounts of pyrrhotite-based tailings produced using autochthonous Thiobacilli.

Three main conclusions were conceived through the testwork performed:

1. The role of copper-containing tailings in nickeliferous tailings disposal.
2. The potential of short bioleach retention times.
3. The concept of a reverse flotation using bioconditioning.

4.1 Tailings Discard

The presence of copper, while doing nothing to enhance nickel solubilization, appeared to contribute to overall lower final pH values of the leach solutions tested. If this laboratory-scale finding can be transposed to the design of tailings discard piles, the storage of chalcopyrite-containing tailings may cause an increased rate of acid mine drainage production from nickel mineral-containing tailing compounds. The resulting low pH would therefore have a considerable effect on the remaining metal concentrations of the tailings. While this claim is based entirely on a correlation between pH behabior and nickel leaching, the direct consequences warrant further investigations.

4.2 Short Leach Times

The highest rate of nickel extractions were found consistently within the initial 24-48 hour start up period. To compliment this finding, the total percentage of nickel leached was highest using a single strain of Thiobacillus ferrooxidans which is capable of maintaining the necessary oxidizing ferric iron concentrations through the energy yielding ferrous to ferric iron oxidation. Shorter leaching times to obtain maximum nickel extractions should be expected with the optimization of various physicochemical parameters.

Increased aeration did show less acid consumption while high pulp densities of pyrrhotite tailings showed significant concentrations of nickel leached. Further improvements in kinetics and recoveries would make bioleaching of nickel from pyrrhotite-pentlandite tailings a potentially viable process.

4.3 Reverse Flotation Potential

Although long blank conditioning times tended to out perform the bioconditioning tests for pentlandite recoveries, the high recoveries of pyrrhotite in a bioconditioned acidic medium have suggested the potential for reverse flotation to suppress pentlandite. Higher frother doses favoured nickel grade and recovery and as such, reagent alteration and other subtle changes in process development may allow for needed improvement.

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APPENDIX I: Tables 1 to 26

Table 1
Falconbridge Sample Sites

ORTECH Identification		
S-1, S-2, S-3,	Slag pond aqueous	
S-4, S-5, S-6	Slag pond mud sediment near cattail marsh	
H-1, H-2, H-3,	Hard cap from old tailings pile	
H-4, H-5	Mud sediment from cattail marsh around old tails pile	
T-1	Fecunis tailings sediment	
T-2	Hardy Lake tailings sediment	
0-1	Moose Lake treatment plant	pH 3.5 aqueous
0-2	Moose Lake treatment plant	pH 3.5 aqueous
0-3	Cranberry Lake aqueous	pH 3.5
0-4	Fecunis tailings before the dam	
0-5	Fraser yard drainage to Fecunis	
0-6	Fraser yard drainage to Fecunis with sediment	
0-7	Tails at Dam S-4	
0-8	Strathcona tails landfill	
0-9	Tails discharge to 0-7, 0-8	
0-10	Onaping mine water	
0-11	Onaping mine pond water inflow with greywater	
M-1	Final tails (Strathcona mill)	
M-2	Scavenger concentrate (Strathcona mill)	
M-3	Copper thickener overflow (Strathcona mill)	
M-4	Nickel thickener overflow (Strathcona mill)	
M-5	Non-magnetics thickener feed to non-magnetics flotation (Strathcona mill)	
M-6	Non-magnetics tailings	
M-7	Pyrrhotite tails - high magnetics	

Table 2

Details of sulphate Reducing Bacteria Isolations

ORTECH ID Number	FBG Environment Source	blackening of lactate sulfate medium	Hungate roll-tube isolations	blackening of isolation and maint. medium
H-1	hard cap	No	--	--
H-5, H-4	black sediment mud	Yes	Yes	Yes
H-3	brown sediment mud	No	--	--
T-1, T-2	tailings sediment	No	--	--
0-11	mine pond grey water sediments	No	--	--
S-5	conservation area sediment from marsh	Yes	Yes	Yes
S-4, S-6	slag pile marshy area sediment	Yes	Yes	Yes
H-2	old tailings pile sediment area	Yes	Yes	Yes

Table 3

Summary of Bacterial Isolates from Various FBG Environments

Abbrev.: NA Nutrient Agar
SX Sabouraud Destrose Agar
TGE Tryptone Glucose Extract Agar
MA-1 Malic Acid [1 g/L] Agar

Sample Locale	Isolation Medium	Gram Stain (+)/(-)	Morphology	Excess Extracellular Polysaccharide Production
Strathcona non-magnetic tails	NA	(-)	rods non motile	(-)
Fraser yard drainage sediments	TGE	(-)	rods non motile	(-)
Onaping mine water	NA	(-)	rods non motile	(-)
Copper thickener overflow	TGE	(-)	rods non motile	(-)
Cranberry Lake water	TGE	(-)	spheres non motile	(-)
Strathcona tails discharge	SX	(-)	rods motile	(+)
Fraser Yard drainage	NA	(+/-)	large spheres yeast(?)	(+)
Cranberry Lake water	TGE	(-)	rods non motile	(-)
Cranberry Lake water	TGE	(+)	spheres motile	(+)
Fraser Yard drainage	NA	(-)	rods motile	(-)
Nickel Thickener overflow	TGE	(-)	spheres non motile	(-)
Nickel Thickener overflow	SX	(+/-)	large spheres yeast(?)	(+)
Moose Lake treatment plant	MA-1 MA-1	(+) (+)	spheres, non motile rods, non motile	(-) (-)

Table 4

Thiobacillus ferrooxidans pH Behavior During Growth Adaption in Pyrrhotite Tailings

Medium Conditions: M9K salts (80%) inoculum (10%)

Culture	Sample locale	% tails (w/v)	Initial pH	After 12N H_2SO_4	13 Days pH	20 Days pH
SM-4	ORTECH in house	11	4.90	2.25	3.94	3.80
Fraser	Yard drainage to Strathcona	13.2	5.00	2.30	4.05	3.92
Fecunis	Tails pond to Strathcona	11.4	5.45	2.25	3.93	3.85
0-1	Moose Lake Treatment plant	7.8	5.10	2.60	4.00	3.94
0-3	Cranberry Lake	8.3	5.70	2.30	4.08	4.00
0-7	Tails at Dam S-4	7.6	5.30	2.50	4.03	3.94
0-9	Tails discharge to Strathcona	9.7	5.00	2.70	3.75	3.07
Slag	Slag pile run-off	7.5	5.25	2.60	4.10	4.05
Control	N/A	10.5	7.10	2.30	4.08	3.96

Table 5

Thiobacillus thiooxidans pH Behavior During Growth on Elemental Sulphur

Culture	Sample locale	Initial pH	1 Day pH	5 Day pH	9 Days pH	13 Days pH
M - 1	Strathcona final tails	2.04	2.08	1.66	1.52	1.34
M - 5	Non-magnetics thickener overflow	1.88	1.83	1.50	1.45	1.30
0 - 9	Tails discharge to Strathcona	2.02	1.99	1.65	1.63	1.29

Table 6

Trial 1 - Bioleached Ni Values from PO Tails Using Thiobacillus ferrooxidans

Thiobacillus ferrooxidans Culture	PO Tails Pulp Density (% w/v)	ppm Ni in Unleached Sample	Day 0		Day 1		Day 2		Day 6		Day 14		Day 28	
			Ni in sol. (ppm)	% Extrac.	Ni in sol. (ppm)	% Extrac.	Ni in sol. (ppm)	% Extrac.	Ni in sol. (ppm)	% Extrac.	Ni in sol. (ppm)	% Extrac.	Ni in sol. (ppm)	% Extrac.
Sterile Control-1	7.5	510	1.0	0.2	26	5.1	40	7.8	69	13.5	95	18.6	125	24.5
Sterile Control-2	7.3	496	1.2	0.2	24	4.8	38	7.7	68	13.7	95	19.2	113	22.7
Slag	7.5	510	11	2.2	59	11.6	76	14.9	130	25.5	175	34.3	230	45.0
Fecunis	7.5	510	12	2.4	59	11.6	89	17.5	140	27.5	190	37.3	240	47.0
Fraser	7.4	503	19	3.8	73	14.5	73	14.5	8.2	16.3	165	32.8	220	43.7
SM-4	7.5	510	17	3.3	65	12.7	73	14.3	150	29.4	190	37.3	250	49.0
0-1	7.5	510	broken	broken	50	9.8	65	12.7	115	22.5	170	33.3	230	45.0
0-3	7.1	483	8	1.7	55	11.4	75	15.5	140	29.0	185	38.3	250	51.7
0-7	7.2	490	7	1.4	44	9.0	61	12.4	120	24.5	160	32.7	220	44.8
0-9(1)	7.3	496.4	broken	broken	59	11.9	77	15.5	135	27.2	170	34.3	235	47.3
0-9(2)	7.3	496.4	5	2.0	39	7.9	51	10.3	95	19.2	125	25.2	250	50.3

Table 7

Trial 1 - Bioleached Fe Values from PO Tails Using Thiobacillus ferrooxidans

Thiobacillus ferrooxidans Culture	PO Tails Pulp density (% w/v)	Day 0		Day 1		Day 2		Day 6		Day 14		Day 28	
		Fe in solution (ppm)	Ni:Fe	Fe in solution (ppm)	Ni:Fe	Fe in solution (ppm)	Ni:Fe	Fe in solution (ppm)	Ni:Fe	Fe in solution (ppm)	Ni:Fe	Fe in solution (ppm)	Ni:Fe
Sterile Control - 1	7.5	0.05	20	430	0.060	850	0.047	1520	0.045	1820	0.052	940	0.132
Sterile Control - 2	7.3	0.10	12	520	0.046	830	0.046	1490	0.046	1850	0.051	890	0.126
Slag	7.5	30	0.377	830	0.071	1330	0.057	1820	0.071	1920	0.091	1080	0.212
Fecunis	7.5	93	0.129	830	0.071	1390	0.064	1900	0.074	2140	0.089	1230	0.195
Fraser	7.4	96	0.198	940	0.078	1780	0.041	1800	0.046	1970	0.084	1100	0.200
SM-4	7.5	66	0.258	800	0.081	1400	0.052	1690	0.089	1870	0.102	1040	0.240
0-1	7.5	broken	broken	840	0.060	1350	0.048	1540	0.075	1920	0.089	1080	0.212
0-3	7.1	10	0.800	890	0.062	1220	0.061	1800	0.078	1930	0.096	1110	0.225
0-7	7.2	19	0.368	830	0.053	1140	0.054	1740	0.069	1790	0.089	2050	0.107
0-9(1)	7.3	broken	broken	1170	0.050	1480	0.052	2070	0.065	2530	0.067	2750	0.085
0-9(2)	7.3	94	0.053	970	0.040	1440	0.035	2290	0.041	3670	0.034	1150	0.217

Table 8

Trial 2 - Bioleached Ni Values from PO Tails Using T. ferrooxidans and T. thiooxidans

T. ferrooxidans (0-9) T. thiooxidans Culture	PO Tails Pulp Density (% w/v)	ppm Ni in Unleached Sample	Day 0		Day 1		Day 2		Day 6		Day 14		Day 28	
			Ni in sol. (ppm)	% Extrac.	Ni in sol. (ppm)	% Extrac.	Ni in sol. (ppm)	% Extrac.	Ni in sol. (ppm)	% Extrac.	Ni in sol. (ppm)	% Extrac.	Ni in sol. (ppm)	% Extrac.
Sterile Control	10	730	5	0.68	19	2.6	27	3.7	52	7.1	80	11.0	120	16.4
Slag	10.1	737	17	2.3	40	5.4	40	5.4	85	11.5	140	19.0	200	27.1
Fecunis	10	730	12	1.6	34	4.7	42	5.8	73	10.0	115	15.8	335	45.9
Fraser	9.7	708	27	3.8	35	4.9	34	4.8	86	12.1	160	22.6	215	30.4
SM-4	9.2	672	27	4.0	26	3.9	broken	broken	69	10.3	120	17.9	175	26.0
0-1	7.5	510	broken	broken	50	9.8	65	12.7	115	22.5	170	33.3	230	45.0
0-3	9.0	657	11	1.7	32	4.9	38	5.8	69	10.5	120	18.3	180	27.4
0-7	9.1	664	22	3.3	28	4.2	32	4.8	67	10.1	110	16.6	165	24.9
0-9	9.1	664	12	1.8	27	4.1	35	5.3	broken	broken	125	18.8	290	43.7

Table 9

Trial 2 - Bioleached Fe Values from PO Tails Using Thiobacillus ferrooxidans

T. ferrooxidans (0-9) T. thiooxidans Culture	PO Tails Pulp density (% w/v)	Day 0		Day 1		Day 2		Day 6		Day 14		Day 28	
		Fe in solution (ppm)	Ni:Fe	Fe in solution (ppm)	Ni:Fe	Fe in solution (ppm)	Ni:Fe	Fe in solution (ppm)	Ni:Fe	Fe in solution (ppm)	Ni:Fe	Fe in solution (ppm)	Ni:Fe
Sterile Control	10	120	0.042	350	0.054	620	0.043	1190	0.044	1750	0.046	2000	0.060
Slag	10.1	870	0.020	1700	0.024	1370	0.029	2100	0.040	2650	0.053	9000	0.022
Fecunis	10	1030	0.017	1900	0.018	1290	0.033	1950	0.045	4300	0.038	7750	0.043
Fraser	9.7	780	0.035	1800	0.019	1500	0.023	1930	0.045	4300	0.037	9750	0.022
SM-4	9.1	950	0.018	1900	0.017	1390	0.028	2550	0.022	4500	0.019	9500	0.016
0-1	9.2	830	0.033	1820	0.014	broken	broken	1650	0.042	2500	0.048	7250	0.024
0-3	9.0	1020	0.011	1820	0.018	1350	0.028	1390	0.050	4150	0.029	9250	0.019
0-7	9.1	1730	0.013	1680	0.017	1370	0.023	1750	0.038	3850	0.029	8500	0.019
0-9	9.1	2030	0.006	1030	0.026	1590	0.022	broken	broken	7370	0.017	18800	0.015

Table 10

Trial 3: Bioleach Ni Values from H_2SO_4 - Pretreated PO Tails, Using T. ferrooxidans and T. thiooxidans

T. ferrooxidans & T. thiooxidans (0-9) cultures	Leaching Conditions	PO Tails Pulp Density (% w/v)	Ni in Unleached Sample (ppm)	Day 0		Day 1		Day 2		Day 6		Day 14		Day 21	
				Ni in Sol. (ppm)	% Extrac.	Ni in Sol. (ppm)	% Extrac.	Ni in Sol. (ppm)	% Extrac.	Ni in Sol. (ppm)	% Extrac.	Ni in Sol. (ppm)	% Extrac.	Ni in Sol. (ppm)	% Extrac.
Sterile Control 50 mL / 250 mL medium flask	60 ppm Cu	8.5	637	1.4	0.2	2	0.3	5	0.8	10	1.5	20	3.1	17	2.7
	120 ppm Cu	10.5	787	2.7	0.3	4	0.5	7	0.9	15	1.9	20	2.5	21	2.7
	Low p.d.*	4.9	367	2.5	0.7	15	4.1	25	6.8	35	9.5	60	16.3	61	16.6
	Mod. p.d.*	11.3	847	3.0	0.4	25	3.0	40	4.7	60	7.1	100	11.8	113	13.3
SM-4 50 mL / 250 mL medium flask	60 ppm Cu	9.6	720	27	3.7	30	4.2	38	5.3	50	6.9	75	10.4	75	10.4
	120 ppm Cu	10.4	780	27	3.5	40	5.1	35	4.5	50	6.4	90	11.5	89	11.4
	Low p.d.	5.3	397	24	6.0	30	7.6	30	7.6	55	13.9	95	24.0	104	26.2
	Mod. p.d.	7.8	585	29	5.0	30	5.1	50	8.5	90	15.4	120	20.5	145	24.8
0-3 50 mL / 250 mL medium flask	60 ppm Cu	7.2	540	29	5.4	35	6.5	40	7.4	45	8.3	70	13	85	15.7
	120 ppm Cu	8.3	622	25	4.0	50	8.0	35	5.6	55	8.8	85	13.7	125	20.1
	Low p.d.	5.2	390	20	5.1	35	9.0	45	11.5	50	12.8	90	23.1	229	58.7
	Mod. p.d.	9.7	730	21	2.9	35	4.8	65	8.9	85	11.6	145	19.9	175	24.0
Fecunis 50 mL / 250 mL medium flask	60 ppm Cu	12.3	922	20	2.2	38	4.1	45	4.9	125	13.6	160	17.4	191	20.7
	120 ppm Cu	13.8	1035	25	2.4	45	4.3	50	4.8	75	7.2	110	10.6	122	11.8
	Low p.d.	8.8	660	17	2.6	43	6.5	40	6.1	65	9.8	85	12.9	105	16.0
	Mod. p.d.	11.7	882	10	1.1	40	4.5	50	5.7	80	9.1	110	12.5	128	14.5
Fecunis 100 mL / 250 mL medium flask	60 ppm Cu	10.6	787	18	2.3	38	4.8	40	5.1	60	7.6	80	10.2	93	11.9
	120 ppm Cu	9.9	742	26	3.5	35	4.7	35	4.7	55	7.4	85	11.5	96	12.9
	60 ppm Cu'a'	9.6	720	36	5.0	45	6.7	55	7.6	80	11.1	105	14.6	110	15.3
	Low p.d.	6.1	457	23	5.0	35	7.7.	40	8.8	60	13.1	90	20.0	104	22.8
	Mod. p.d.	11.0	825	17	2.1	45	5.5	60	7.3	110	13.3	160	19.4	188	22.8
	Low p.d.'a'	3.6	270	27	10.0	35	13.0	35	13.0	55	20.4	70	26.0	96	35.6

p.d.* = pulp density Mod. = Moderate a = untreated ore

Table 11

Trial 3: Bioleach Fe Values from H_2SO_4 - Pretreated PO Tails Using T. ferrooxidans and T. thiooxidans

T. ferrooxidans & T. thiooxidans (0-9) cultures	Leaching Conditions	Day 0		Day 1		Day 2		Day 6		Day 14		Day 21	
		Fe in Sol. (ppm)	Ni:Fe	Fe in Sol. (ppm)	Ni:Fe	Fe in Sol. (ppm)	Ni:Fe	Fe in Sol. (ppm)	Ni:Fe	Fe in Sol. (ppm)	Ni:Fe	Fe in Sol. (ppm)	Ni:Fe
Sterile Control 50 mL/250 mL medium flask	60 ppm Cu	220	0.006	750	0.003	400	0.012	500	0.020	900	0.022	1080	0.016
	120 ppm Cu	390	0.007	1100	0.004	550	0.013	750	0.020	1050	0.019	1210	0.017
	Low p.d.*	460	0.005	300	0.050	1350	0.019	2900	0.012	5150	0.012	5300	0.012
	Mod. p.d.*	725	0.004	450	0.055	2200	0.018	4800	0.012	8900	0.011	9650	0.012
SM-4 50 mL/250 mL medium flask	60 ppm Cu	1530	0.018	1300	0.023	1300	0.029	2050	0.024	3500	0.021	3770	0.020
	120 ppm Cu	1530	0.018	1800	0.011	1250	0.028	1900	0.026	4100	0.022	4700	0.019
	Low p.d.	1440	0.017	1100	0.027	1550	0.018	3400	0.016	6250	0.015	7200	0.014
	Mod. p.d.	1710	0.017	1050	0.029	2200	0.023	4100	0.022	8500	0.014	10100	0.014
0-3 50 mL/250 mL medium flask	60 ppm Cu	1260	0.023	1250	0.028	900	0.044	1950	0.023	3500	0.020	3900	0.022
	120 ppm Cu	900	0.028	1950	0.026	950	0.037	2450	0.023	5250	0.016	8200	0.015
	Low p.d.	1160	0.017	800	0.044	1850	0.024	2850	0.018	6300	0.014	5900	0.039
	Mod. p.d.	1700	0.012	850	0.041	2200	0.030	5300	0.016	10000	0.015	11800	0.015
Fecunis 50 mL/250 mL medium flask	60 ppm Cu	1570	0.013	1450	0.026	1600	0.028	3650	0.034	6600	0.024	8550	0.022
	120 ppm Cu	1360	0.018	1500	0.030	1450	0.034	3550	0.021	6300	0.017	7450	0.016
	Low p.d.	1290	0.013	1550	0.028	2150	0.019	4000	0.016	6000	0.014	7350	0.014
	Mod. p.d.	1450	0.007	1650	0.024	2400	0.021	4850	0.016	7700	0.014	8800	0.015
Fecunis 100 mL/250 mL	60 ppm Cu	1480	0.012	1250	0.030	1400	0.029	2300	0.026	4200	0.019	4850	0.019
	120 ppm Cu	1000	0.026	1050	0.033	1300	0.027	2200	0.025	4500	0.019	5500	0.017
	60 ppm Cu"a"	840	0.043	750	0.060	1100	0.050	2700	0.030	4650	0.023	5550	0.020
	Mod. p.d.	700	0.024	1650	0.027	2300	0.026	4000	0.028	8500	0.019	10800	0.017
	Low p.d."a"	490	0.055	1000	0.035	1100	0.032	2150	0.026	3750	0.019	5100	0.019
	Low p.d.	1320	0.017	1450	0.024	2000	0.020	3650	0.016	5700	0.016	7100	0.015

p.d.* = pulp density Mod. = Moderate a = untreated ore

Table 12

Trial 4 - Bioleached Ni Values at High Pulp Densities using *I. ferrooxidans* and *I. thiooxidans*

Leach Conditions	PO Talls Pulp Density (% w/v)	ppm Ni in Unleached Sample	Day 0		Day 2		Day 6		Day 14		Day 21	
			Ni in sol. (ppm)	% Extrac.	Ni in sol. (ppm)	% Extrac.	Ni in sol. (ppm)	% Extrac.	Ni in sol. (ppm)	% Extrac.	Ni in sol. (ppm)	% Extrac.
Untreated Ore	19.6	1428	33	2.3	160	11.2	280	19.6	370	26.0	475	33.3
Untreated Ore	26.1	1903	29	1.5	186	9.8	275	14.5	375	19.7	470	24.7
Acid Treated Ore/ 60 ppm Cu	21.2	1590	46	2.9	83	5.2	140	8.8	330	20.8	495	31.1
Acid Treated Ore/ 60 ppm Cu	29.8	2238	44	2.0	110	4.9	185	8.3	310	13.9	430	19.2
Acid Treated Ore	21.1	1585	34	2.1	127	8.0	185	11.7	275	17.4	330	20.9
Acid Treated Ore	32.9	2466	16	0.6	150	6.1	250	10.1	390	15.8	515	20.9
Untreated Ore/ 60 ppm Cu	18.0	1317	41	3.1	96	7.3	160	12.1	375	28.5	590	44.8
Control	29.7	2167	0.42	0.02	98	4.5	165	7.6	255	11.8	335	15.5

Table 13

Trial 4 - Bioleached Fe Values at High Pulp Densities Using T. ferrooxidans and T. thiooxidans

Leach Conditions	Day 0		Day 2		Day 6		Day 14		Day 21	
	Fe in Solution (ppm)	Ni:Fe	Fe in Solution (ppm)	Ni:Fe	Fe in Solution (ppm)	Ni:Fe	Fe in .Solution (ppm)	Ni:Fe	Fe in Solution (ppm)	Ni:Fe
Untreated Ore	1350	0.024	3800	0.042	7300	0.038	13000	0.028	12700	0.037
Untreated Ore	1400	0.021	3850	0.048	7800	0.035	13200	0.028	14400	0.033
Acid Treated Ore 60 ppm Cu	2300	0.020	3150	0.026	6100	0.023	11000	0.030	12000	0.041
Acid Treated Ore 60 ppm Cu	2450	0.018	3600	0.031	6400	0.029	8800	0.035	8600	0.050
Acid Treated Ore	2350	0.014	4800	0.026	8200	0.023	16700	0.016	24500	0.013
Acid Treated Ore	2700	0.006	4500	0.033	8700	0.029	12200	0.032	12500	0.041
Untreate Ore 60 ppm Cu	1250	0.033	2800	0.034	5700	0.028	11200	0.033	15000	0.039
Control	63	0.007	2650	0.037	7400	0.022	10500	0.024	11500	0.029

Table 14

Pyrrhotite Tails Bioleaching Rates

Thiobacillus ferrooxidans Trial 1	Pulp Density wt. %	Maximum % Ni release (within 24-30 hrs. except as noted)	Maximum minus control	% Ni release per day for 14 days	Minus control 14 days	Ni:Fe 14 days	% release per day for 28 days/ (total Ni release)	Minus control 28 days	Ni:Fe 28 days	Total acid added g 12N H_2SO_4 100g tails	Final pH after 28 days	Liquor colour after 28 days
Control	7.37	4.75	–	1.34	–	0.052	0.83 (23.5)	–	0.130	1.61	3.70	red-brown
Slag	7.50	9.40	4.65	2.29	0.85	0.091	1.53 (45.0)	0.70	0.212	1.61	3.78	red-brown
Fecunis	7.50	9.20	4.45	2.49	1.15	0.089	1.59 (47.0)	0.76	0.195	1.61	3.73	red-brown
Fraser	7.40	10.70	5.95	2.07	0.73	0.084	143 (43.7)	0.60	0.200	1.63	3 69	red-brown
SM-4	7.50	9.40	4.65	2.43	1.09	0.102	1.63 (49.0)	0.80	0.240	1.61	3.76	red-brown
0 - 1	7.50	7.80	3.05	2.24	0.90	0.089	1.54 (45.0)	0.71	0.212	1.61	3.76	red-brown
0 - 3	7.15	9.70	2.95	2.61	1.27	0.096	1.79 (51.7)	0.96	0.225	1.61	3.78	red-brown
0 - 7	7.16	7.60	2.85	2.24	0.90	0.089	1.55 (44.8)	0.72	0.107	1.73	3.70	red-brown
0 - 9	7.30	9.90	5.15	2.31	1.97	0.034	1.63 (47.3)	0.80	0.217	1.81	3.62	red-brown
0 - 9 (dupl.)	7.30	5.90	1.15	1.66	0.32	0.067	1.73 (50.3)	0.90	0.085	1.61	2.53	red-brown
Trial 2												
Control	10.0	1.92 (1.06 to 6 days)	–	0.74	–	0.046	0.56 (16.4)	–	0.060	1.06	3.88	red-orange
Slag	10.1	3.10	1.18	1.19	0.45	0.053	0.89 (27.1)	0.33	0.022	1.05	1.89	yellow-orange
Fecunis	10.0	3.10	1.18	1.01	0.27	0.038	1.58 (45.9)	1.02	0.043	1.06	2.24	red-brown
Fraser	9.7	1.38 (6 days)	0.32	1.34	0.60	0.037	0.95 (30.4)	0.39	0.022	1.09	1.93	yellow-orange
SM-4	9.1	2.20	0.28	0.73	0.00	0.019	0.74 (23.3)	0.18	0.016	1.16	2.32	grey-black
0 - 1	9.2	1.05 (6 days)	0.00	0.99	0.25	0.048	0.79 (26.0)	0.23	0.024	1.15	2.01	yellow-orange
0 - 3	9.0	3.20	1.28	1.19	0.45	0.029	0.92 (27.4)	0.36	0.019	1.18	1.83	yellow-brown
0 - 7	9.1	1.13	0.07	0.95	0.21	0.029	0.77 (24.9)	0.21	0.019	1.16	2.10	yellow-brown
0 - 9	9.1	2.30 (6 days)	0.38	1.21	0.47	0.017	1.50 (47.3)	0.94	0.015	1.16	2.63	red-brown

Table 15

Pyrrotite Tails Bioleach Rates

Leaching Conditions Trial 3	Maximum % Ni release [time (hrs.) as noted]	% Ni release per day for 14 days	% Ni release per day for 21 days	Total acid added g 12N H_2SO_4 per 100g tails	Final pH after 21 days	Liquor colour after 21 days
Control (Sterile)						
60 ppm Cu	0.30(48)	0.21	0.12	0.15	2.70	grey
120 ppm Cu	0.30(48)	0.16	0.11	0.17	2.67	grey
Low p.d.	3.4(24)	1.11	0.76	2.88	4.02	grey orange
Mod. p.d.	2.6(24)	0.81	0.61	2.35	4.03	grey orange
SM-4/T.t.						
60 ppm Cu	0.8(48)	0.48	0.32	1.10	2.85	grey orange
120 ppm Cu	1.6(24)	0.57	0.38	1.36	2.75	grey orange
Low p.d.	1.6(24)	1.29	0.96	0	2.10	grey orange
Mod. p.d.	1.75(48)	1.11	0.84	1.13	1.68	grey orange
0-3/T.t.						
60 ppm Cu	1.2(24)	0.54	0.49	0.98	3.22	grey orange
120 ppm Cu	4.0(24)	0.69	0.81	0.42	1.60	grey orange
Low p.d.	3.9(24)	1.29	2.55	0.34	2.31	red brown
Mod. p.d.	3.0(48)	1.21	1.00	1.46	1.43	grey orange
Fecunis/T.t.						
60 ppm Cu	1.9(24)	1.09	0.88	0.72	1.42	grey orange
120 ppm Cu	1.9(24)	0.59	0.48	1.67	1.84	grey
Low p.d.	3.9(24)	0.74	0.64	1.20	1.60	grey orange
Mod. p.d.	3.4(24)	0.81	0.64	0.91	1.60	grey orange
Fecunis/T.t. (100 mL)						
60 ppm Cu	2.5(24)	0.56	0.46	3.17	3.44	brown orange
120 ppm Cu	1.2(24)	0.57	0.45	3.21	2.22	grey
60 ppm Cu (reg. ore)	1.7(24)	0.69	0.49	4.42	2.62	orange grey
Low p.d.	2.2(24)	1.07	0.85	0.87	1.82	orange grey
Mod. p.d.	3.4(24)	1.24	0.99	3.37	1.46	orange grey
Low p.d. (reg. ore)	3.0(24)	1.14	1.22	1.47	1.94	orange grey

Table 16

Pyrrotite Tails Bioleach Rates

Leaching Conditions Trial 4	Maximum % Ni release (within 48 hrs.)	% Ni release per day for 14 days	% Ni release per day for 21 days	Total acid added g 12N H_2SO_4 per 100g tails	Final pH after 21 days	Liquor colour after 21 days
T.f./T.t. Untreated Ore (20% pd)	4.45	1.69	1.48	3.77	2.86	Orange
Untreated Ore (30% pd)	8.3	1.30	1.10	3.05	2.86	Light Orange
Acidified Ore 60 ppm Cu (20% pd)	3.3	1.28	1.34	2.78	2.65	Orange
Acidified Ore 60 ppm Cu (30% pd)	2.9	0.85	0.82	2.23	3.12	Light Orange
Acidified Ore (20% pd)	6.1	1.09	0.90	4.00	1.45	Grey
Acidified Ore (30% pd)	5.5	1.09	0.97	2.65	3.24	Orange
Untreated Ore 60 ppm Cu (20% pd)	4.2	1.81	1.96	3.69	2.52	Orange
Control Untreated Ore (30% pd)	4.5	0.84	0.74	3.54	3.40	Light Orange

Table 17

pH Behaviour of Bioleach Trials 3 and 4 (for Figures 11-21)

		Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	10	Day 11	Day 13	Day 14	Day 21
Trial 3																
Fig. 11	Control	2.28	2.46	2.56	2.59		2.85	2.92/2.08		2.15	2.19		2.20	2.31	2.33	2.70
	0-3	1.90	2.17	2.36	3.20/2.22		3.56/2.22	2.95/1.96		2.15	2.23		2.28	2.51	2.72	3.22
Fig. 12	Control	2.22	2.37	2.50	2.57		2.92	3.05/2.08		2.12	2.16		2.20	2.30	2.33	2.67
	0-3	1.87	2.13	2.30	2.76		3.40/2.27	2.76/2.14		1.94	1.60		1.50	1.53	1.51	1.60
Fig. 13	Control	2.31	4.62/2.37	4.35/1.96	2.68		4.28/2.05	2.45		3.31/2.20	2.58		3.50/1.98	2.28	2.55	4.02
	0-3	1.84	4.56/2.50	4.45/1.99	4.24/2.30		4.02/2.03	3.65/2.20		3.55/2.20	2.22		1.47	1.41	1.38	1.43
Fig. 15	Fecunis 50	1.90	2.37	3.65/2.32	2.40		3.40/2.27	3.40/1.59		1.96	2.05		1.90	1.65	1.52	1.42
	Fecunis 100	1.98	2.25	2.71	3.57/2.14		3.50/2.27	3.35/2.33		3.43/2.30	3.28/2.31		3.40/2.36	3.35/2.26	2.68/2.21	3.44
	Fecunis 100 (Reg. Ore)	2.25	3.73/2.22	3.65/2.25	3.53/2.22		3.45/2.26	3.25/2.37		3.43/2.39	3.31/2.42		3.36/2.38	3.35/2.26	2.97/2.12	2.62
Fig. 16	Fecunis 50	1.93	4.70/2.18	4.60/2.10	3.17/1.96		2.82	2.20		1.80	1.72		1.62	1.65	1.63	1.60
	Fecunis 100	1.90	3.63/2.20	2.88	2.89		2.15	2.02		1.84	1.80		1.75	1.78	1.77	1.82
	Fecunis (Reg. Ore)	2.12	2.74	2.70	2.47/1.92		1.92	1.90		1.87	1.88		1.85	1.87	1.82	1.94
Trial 4																
Fig. 18	Control Untreated Ore	6.07/2.13		4.35/2.00	4.08/2.11	3.96/2.00	3.85/2.07	3.71/2.13	3.65/2.04			3.67/2.10			3.53	3.40
	60 ppm Cu	3.21/2.12		3.46/2.20	3.27/2.15	3.14/2.11	3.10/2.17	3.05/2.12	3.02/2.06			2.98/2.22			2.97	2.52
Fig. 19	Acid Treated Ore	3.43/2.12		4.41/1.80	3.77/2.27	3.70/2.13	3.60/2.10	3.36/2.09	2.90/2.13			3.01/2.13			1.80	1.45
Fig. 20	Acid Treated Ore 60 ppm Cu	2.87/2.15		3.51/2.20	3.43/2.19	3.06/2.15	3.07/2.08	3.02/2.15	2.97/2.17			3.03/2.13			3.06	2.65
Fig. 21	Untreated Ore	4.44/2.14		4.41/2.14	3.78/2.20	3.16/2.19	3.17/2.16	3.10/2.20	3.10/2.18			3.08/2.16			3.05	2.86

Table 18

Blank Conditioning for 20 Minutes

PROGRAM: SCALP FLOTATION / ORTECH
TEST 1 BASELINE

PRODUCTS	WT	WT PERCENT	ASSAYS NI	CU	S	MINERAL ASSAYS PN	CP	PO	GN	PO/PN RATIO	%NI as NiS
CONC.1	3.54	3.54	2.06	0.42	14.00	5.16	1.22	29.82	63.81	5.78	5.88
CONC.2	1.33	1.33	2.47	0.69	22.20	5.95	2.00	49.07	42.98	8.25	4.48
CONC.3	3.76	3.76	2.58	2.00	23.80	6.24	5.80	49.52	38.44	7.93	4.62
TAILS.	91.37	91.37	1.01	0.17	23.60	1.77	0.49	57.39	40.35	32.36	1.71
CALC. HEAD	100.00	100.00	1.13	0.25	23.25	2.12	0.74	56.01	41.14	26.46	1.94

	DISTRIBUTION NI	CU	S	MINERAL DISTRIBUTION PN	CP	PO	GN
CONC.1	6.48	5.84	2.13	8.62	5.84	1.88	5.49
CONC.2	2.92	3.60	1.27	3.74	3.60	1.17	1.39
CONC.3	8.62	29.54	3.85	11.09	29.54	3.32	3.51
FIN.TAIL.	81.98	61.02	92.75	76.55	61.02	93.63	89.61
CALC.HEAD	100.00	100.00	100.00	100.00	100.00	100.00	100.00

CUMULATIVE PRODUCTS	WT	WT PERCENT	ASSAYS NI	CU	S	MINERAL ASSAYS PN	CP	PO	GN	PO/PN RATIO	%NI as NiS
CONC.1	3.54	3.54	2.06	0.42	14.00	5.16	1.22	29.82	63.81	5.78	5.88
CONC.1+2	4.87	4.87	2.17	0.49	16.24	5.37	1.43	35.08	58.12	6.53	5.35
CONC.1TO3	8.63	8.63	2.35	1.15	19.53	5.75	3.34	41.37	49.54	7.19	4.98
TAILS.	91.37	91.37	1.01	0.17	23.60	1.77	0.49	57.39	40.35	32.36	1.71
CALC. HEAD	100.00	100.00	1.13	0.25	23.25	2.12	0.74	56.01	41.14	25.46	1.94

	DISTRIBUTION NI	CU	S	MINERAL DISTRIBUTION PN	CP	PO	GN
CONC.1	6.48	5.84	2.13	8.62	5.84	1.88	5.49
CONC.1+2	9.40	9.45	3.40	12.35	9.45	3.05	6.88
CONC.1TO3	18.02	38.98	7.25	23.45	38.98	6.37	10.39
TAILS.	81.98	61.02	92.75	76.55	61.02	93.63	89.61
CALC.HEAD	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 19

Blank Conditioning for 20 Minutes

PROGRAM: SCALP FLOTATION / ORTECH
TEST 4 2ND BASELINE

PRODUCTS	WT	WT PERCENT	ASSAYS NI	CU	S	MINERAL ASSAYS PN	CP	PO	GN	PO/PN RATIO	%NI as NiS
CONC.1	1.98	1.98	1.70	0.44	9.00	4.37	1.28	17.85	76.50	4.08	7.54
CONC.2	1.10	1.10	2.27	0.71	19.70	5.50	2.06	43.11	49.33	7.84	4.65
CONC.3	4.17	4.17	2.93	1.97	23.50	7.24	5.71	48.02	39.04	6.64	5.30
TAILS.	92.75	92.75	1.00	0.17	22.20	1.81	0.49	53.84	43.86	29.77	1.80
CALC. HEAD	100.00	100.00	1.11	0.26	21.97	2.13	0.74	52.77	44.36	24.82	2.02

	DISTRIBUTION NI	CU	S	MINERAL DISTRIBUTION PN	CP	PO	GN
CONC.1	3.04	3.40	0.81	4.07	3.40	0.67	3.41
CONC.2	2.25	3.05	0.99	2.85	3.05	0.90	1.22
CONC.3	11.02	32.05	4.45	14.19	32.05	3.79	3.67
FIN.TAIL.	83.69	61.51	93.74	78.99	61.51	94.64	91.69
CALC.HEAD	100.00	100.00	100.00	100.00	100.00	100.00	100.00

CUMULATIVE PRODUCTS	WT	WT PERCENT	ASSAYS NI	CU	S	MINERAL ASSAYS PN	CP	PO	GN	PO/PN RATIO	%NI as NiS
CONC.1	1.98	1.98	1.70	0.44	9.00	4.37	1.28	17.85	76.50	4.08	7.54
CONC.1+2	3.08	3.08	1.90	0.54	12.82	4.78	1.56	26.88	66.79	5.63	6.01
CONC.1TO3	7.25	7.25	2.49	1.36	18.96	6.19	3.95	39.03	50.83	6.31	5.51
TAILS.	92.75	92.75	1.00	0.17	22.20	1.81	0.49	53.84	43.86	29.77	1.80
CALC. HEAD	100.00	100.00	1.11	0.26	21.97	2.13	0.74	52.77	44.36	24.82	2.02

	DISTRIBUTION NI	CU	S	MINERAL DISTRIBUTION PN	CP	PO	GN
CONC.1	3.04	3.40	0.91	4.07	3.40	0.67	3.41
CONC.1+2	5.29	6.45	1.80	6.92	6.45	1.57	4.64
CONC.1TO3	16.31	38.49	6.25	21.11	38.49	5.36	8.31
TAILS.	83.69	61.51	93.74	78.89	61.51	94.64	91.69
CALC.HEAD	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 20

Bioconditioning, 20 Minutes, High Frother Dose

PROGRAM: SCALP FLOTATION / ORTECH
TEST 2 20 min. BIOCONDITIONING, HIGH FROTHER DOSE

PRODUCTS	WT	WT PERCENT	ASSAYS NI	CU	S	MINERAL ASSAYS PN	CP	PO	GN	PO/PN RATIO	%NI as NiS
CONC.1	7.54	7.54	2.66	0.47	28.20	6.20	1.36	64.50	27.94	10.40	3.76
CONC.2	3.77	3.77	2.10	0.79	31.20	4.51	2.29	72.63	20.57	16.10	2.72
CONC.3	6.65	6.65	1.70	1.08	31.50	3.39	3.13	73.58	19.90	21.70	2.21
TAILS.	82.04	82.04	0.89	0.13	19.90	1.60	0.38	48.34	49.68	30.17	1.78
CALC. HEAD	100.00	100.00	1.12	0.24	21.72	2.18	0.71	52.15	44.97	23.95	2.07

	DISTRIBUTION NI	CU	S	MINERAL DISTRIBUTION PN	CP	PO	GN
CONC.1	17.86	14.54	9.79	21.47	14.54	9.33	4.68
CONC.2	7.05	12.22	5.41	7.81	12.22	5.25	1.72
CONC.3	10.07	29.47	9.64	10.36	29.47	9.38	2.94
FIN.TAIL.	65.02	43.76	75.15	60.37	43.76	76.04	90.65
CALC. HEAD	100.00	100.00	100.00	100.00	100.00	100.00	100.00

CUMULATIVE PRODUCTS	WT	WT PERCENT	ASSAYS NI	CU	S	MINERAL ASSAYS PN	CP	PO	GN	PO/PN RATIO	%NI as NiS
CONC.1	7.54	7.54	2.66	0.47	28.20	6.20	1.36	64.50	27.94	10.40	3.76
CONC.1+2	11.31	11.31	2.47	0.58	29.20	5.64	1.67	67.21	25.48	11.92	3.33
CONC.1TO3	17.96	17.96	2.19	0.76	30.05	4.81	2.21	69.57	23.41	14.48	2.94
TAILS.	82.04	82.04	0.89	0.13	19.90	1.60	0.38	48.34	49.68	30.17	1.78
CALC. HEAD	100.00	100.00	1.12	0.24	21.72	2.18	0.71	52.15	44.97	23.95	2.07

	DISTRIBUTION NI	CU	S	MINERAL DISTRIBUTION PN	CP	PO	GN
CONC.1	17.86	14.54	9.79	21.47	14.54	9.33	4.68
CONC.1+2	24.91	26.76	15.20	29.28	25.76	14.58	6.41
CONC.1TO3	34.98	56.24	24.85	39.63	56.24	23.96	9.35
TAILS.	65.02	43.76	75.15	60.37	43.76	76.04	90.65
CALC.HEAD	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 21

Bioconditioning, 20 Minutes

PROGRAM: SCALP FLOTATION / ORTECH
TEST 3 20 min. BIOCONDITIONING, NORMAL FROTHER DOSE

PRODUCTS	WT	WT PERCENT	ASSAYS NI	CU	S	MINERAL ASSAYS PN	CP	PO	GN	PO/PN RATIO	NI as NiS
CONC.1	0.89	0.89	2.68	0.64	31.20	6.13	1.86	71.66	20.35	11.69	3.44
CONC.2	1.55	1.55	2.49	1.07	30.70	5.64	3.10	69.72	21.54	12.37	3.30
CONC.3	11.97	11.97	2.40	0.99	31.50	5.35	2.87	72.18	19.60	13.50	3.09
TAILS.	85.59	85.59	0.90	0.13	23.20	1.48	0.38	56.73	41.41	38.28	1.55
CALC. HEAD	100.00	100.00	1.12	0.25	24.38	2.05	0.73	58.91	38.31	28.73	1.84

	DISTRIBUTION NI	CU	S	MINERAL DISTRIBUTION PN	CP	PO	GN
CONC.1	2.13	2.26	1.14	2.65	2.26	1.08	0.47
CONC.2	3.45	6.58	1.95	4.26	6.58	1.83	0.87
CONC.3	25.65	47.02	15.47	31.22	47.02	14.67	6.13
FIN.TAIL.	68.78	44.14	81.44	61.86	44.14	82.42	92.53
CALC.HEAD	100.00	100.00	100.00	100.00	100.00	100.00	100.00

CUMULATIVE PRODUCTS	WT	WT PERCENT	ASSAYS NI	CU	S	MINERAL ASSAYS PN	CP	PO	GN	PO/PN RATIO	NI as NiS
CONC.1	0.89	0.89	2.68	0.64	31.20	6.13	1.86	71.66	20.35	11.69	3.44
CONC.1+2	2.44	2.44	2.56	0.91	30.88	5.82	2.65	70.43	21.10	12.11	3.35
CONC.1TO3	14.41	14.41	2.43	0.98	31.40	5.43	2.83	71.88	19.86	13.25	3.14
TAILS.	85.59	85.59	0.90	0.13	23.20	1.48	0.38	56.73	41.41	38.28	1.55
CALC. HEAD	100.00	100.00	1.12	0.25	24.38	2.05	0.73	58.91	38.31	28.73	1.84

	DISTRIBUTION NI	CU	S	MINERAL DISTRIBUTION PN	CP	PO	GN
CONC.1	2.13	2.26	1.14	2.65	2.26	1.08	0.47
CONC.1+2	5.58	8.84	3.09	6.92	8.84	2.92	1.34
CONC.1TO3	31.22	55.86	18.55	38.14	55.86	17.58	7.47
TAILS.	68.78	44.14	81.44	61.86	44.14	82.42	92.53
CALC.HEAD	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 22

Bioconditioning, 60 Minutes

PROGRAM: SCALP FLOTATION / ORTECH
TEST 5 60 min. BIOCONDITIONING

PRODUCTS	WT	WT PERCENT	ASSAYS NI	CU	S	MINERAL ASSAYS PN	CP	PO	GN	PO/PN RATIO	%Ni as NiS
CONC.1	5.76	5.76	4.17	2.21	31.90	10.34	6.41	65.93	17.32	6.38	5.46
CONC.2	7.32	7.32	2.04	0.69	32.50	4.29	2.00	76.34	17.38	17.83	2.53
CONC.3	7.98	7.98	1.26	0.29	31.60	2.12	0.84	76.90	20.14	36.29	1.53
TAILS.	78.94	78.94	0.82	0.07	21.00	1.35	0.20	51.46	46.98	38.00	1.55
CALC. HEAD	100.00	100.00	1.14	0.26	23.32	2.15	0.74	56.14	40.97	26.15	1.95

	DISTRIBUTION NI	CU	S	MINERAL DISTRIBUTION PN	CP	PO	GN
CONC.1	21.12	49.69	7.88	27.74	49.69	6.76	2.44
CONC.2	13.13	19.71	10.20	14.59	19.71	8.95	3.10
CONC.3	8.84	9.03	10.82	7.89	9.03	10.93	3.92
FIN.TAIL.	56.91	21.57	71.10	49.79	21.57	72.35	90.54
CALC.HEAD	100.00	100.00	100.00	100.00	100.00	100.00	100.00

CUMULATIVE PRODUCTS	WT	WT PERCENT	ASSAYS NI	CU	S	MINERAL ASSAYS PN	CP	PO	GN	PO/PN RATIO	%Ni as NiS
CONC.1	5.76	5.76	4.17	2.21	31.90	10.34	6.41	65.93	17.32	6.38	5.46
CONC.1+2	13.08	13.08	2.98	1.36	32.24	6.95	3.94	71.76	17.35	10.33	3.78
CONC.1TO3	21.06	21.06	2.33	0.95	31.99	5.12	2.77	73.70	18.41	14.40	2.95
TAILS.	78.94	78.94	0.82	0.07	21.00	1.35	0.20	51.46	46.98	38.00	1.55
CALC. HEAD	100.00	100.00	1.14	0.26	23.32	2.15	0.74	56.14	40.97	26.15	1.95

	DISTRIBUTION NI	CU	S	MINERAL DISTRIBUTION PN	CP	PO	GN
CONC.1	21.12	49.69	7.88	27.74	49.69	6.76	2.44
CONC.1+2	34.25	69.40	18.08	42.33	69.40	16.72	5.54
CONC.1TO3	43.09	78.43	28.90	50.21	78.43	27.65	9.46
TAILS.	56.91	21.57	71.10	49.79	21.57	72.35	90.54
CALC.HEAD	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 23

Acidic Bioconditioning, 20 Minutes

PROGRAM: SCALP FLOTATION / ORTECH
TEST 6 ACIDIC BIOCONDITIONING, 20 min.

PRODUCTS	WT	WT PERCENT	ASSAYS NI	CU	S	MINERAL ASSAYS PN	CP	PO	GN	PO/PN RATIO	Ni as NiS
CONC.1	12.67	12.67	1.29	0.74	31.60	2.22	2.15	75.67	19.97	34.03	1.66
CONC.2	15.33	15.33	1.16	0.48	33.30	1.77	1.39	80.97	15.85	45.72	1.40
CONC.3	12.00	12.00	1.04	0.30	32.80	1.45	0.87	80.44	17.24	55.50	1.27
TAILS.	60.00	60.00	1.08	0.08	15.70	2.32	0.23	37.31	60.13	16.08	2.72
CALC. HEAD	100.00	100.00	1.11	0.25	22.46	2.12	0.73	54.04	43.11	25.49	1.98

	DISTRIBUTION NI	CU	S	MINERAL DISTRIBUTION PN	CP	PO	GN
CONC.1	14.67	37.30	17.82	13.29	37.30	17.74	5.87
CONC.2	15.96	29.28	22.72	12.81	29.28	22.97	5.64
CONC.3	11.20	14.32	17.52	8.21	14.32	17.86	4.80
FIN.TAIL.	58.17	19.10	41.93	65.70	19.10	41.43	83.69
CALC.HEAD	100.00	100.00	100.00	100.00	100.00	100.00	100.00

CUMULATIVE PRODUCTS	WT	WT PERCENT	ASSAYS NI	CU	S	MINERAL ASSAYS PN	CP	PO	GN	PO/PN RATIO	Ni as NiS
CONC.1	12.67	12.67	1.29	0.74	31.60	2.22	2.15	75.67	19.97	34.03	1.66
CONC.1+2	28.00	28.00	1.22	0.60	32.53	1.98	1.73	78.57	17.72	39.77	1.51
CONC.1TO3	40.00	40.00	1.17	0.51	32.61	1.82	1.47	79.13	17.57	43.53	1.44
TAILS.	60.00	60.00	1.08	0.08	15.70	2.32	0.23	37.31	60.13	16.08	2.72
CALC. HEAD	100.00	100.00	1.11	0.25	22.46	2.12	0.73	54.04	43.11	25.49	1.98

	DISTRIBUTION NI	CU	S	MINERAL DISTRIBUTION PN	CP	PO	GN
CONC.1	14.67	37.30	17.82	13.29	37.30	17.74	5.87
CONC.1+2	30.63	66.58	40.55	25.10	66.58	40.71	11.51
CONC.1TO3	41.83	80.90	58.07	34.30	80.90	58.57	16.31
TAILS.	58.17	19.10	41.93	65.70	19.10	41.43	83.69
CALC.HEAD	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 24

Bioconditioning, 120 Minutes

PROGRAM: SCALP FLOTATION / ORTECH
TEST 7 120 min. BIOCONDITIONING

PRODUCTS	WT	WT PERCENT	ASSAYS NI	CU	S	MINERAL ASSAYS PN	CP	PO	GN	PO/PN RATIO	%N1 as N1S
CONC.1	5.30	5.30	3.80	2.05	32.50	9.27	5.97	68.71	16.05	7.41	4.87
CONC.2	10.60	10.60	1.89	0.57	33.40	3.79	1.65	79.32	15.24	20.95	2.26
CONC.3	11.70	11.70	1.12	0.22	32.70	1.67	0.64	80.21	17.48	47.90	1.37
TAILS.	72.40	72.40	0.83	0.07	18.70	1.49	0.20	45.57	52.74	30.67	1.76
CALC. HEAD	100.00	100.00	1.13	0.25	22.63	2.16	0.71	54.43	42.70	25.15	2.00

	DISTRIBUTION NI	CU	S	MINERAL DISTRIBUTION PN	CP	PO	GN
CONC.1	17.78	44.38	7.61	22.70	44.38	6.69	1.99
CONC.2	17.59	24.55	15.65	18.55	24.56	15.45	3.78
CONC.3	11.57	10.46	16.91	9.05	10.46	17.24	4.79
FIN.TAIL.	53.05	20.60	59.83	49.70	20.60	60.62	89.43
CALC.HEAD	100.00	100.00	100.00	100.00	100.00	100.00	100.00

CUMULATIVE PRODUCTS	WT	WT PERCENT	ASSAYS NI	CU	S	MINERAL ASSAYS PN	CP	PO	GN	PO/PN RATIO	%N1 as N1S
CONC.1	5.30	5.30	3.80	2.06	32.50	9.27	5.97	68.71	16.05	7.41	4.87
CONC.1+2	15.90	15.90	2.52	1.07	33.10	5.61	3.09	75.78	15.51	13.50	3.09
CONC.1TO3	27.60	27.60	1.93	0.71	32.93	3.94	2.05	77.66	16.35	19.69	2.36
TAILS.	72.40	72.40	0.83	0.07	18.70	1.49	0.20	45.57	52.74	30.67	1.76
CALC. HEAD	100.00	100.00	1.13	0.25	22.63	2.16	0.71	54.43	42.70	25.15	2.00

	DISTRIBUTION NI	CU	S	MINERAL DISTRIBUTION PN	CP	PO	GN
CONC.1	17.78	44.38	7.61	22.70	44.38	6.69	1.99
CONC.1+2	35.38	68.94	23.26	41.25	68.94	22.14	5.78
CONC.1TO3	46.95	79.40	40.17	50.30	79.40	39.38	10.57
TAILS.	53.05	20.60	59.83	49.70	20.60	60.62	89.43
CALC.HEAD	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 25

Blank Conditioning, 120 Minutes

PROGRAM: SCALP FLOTATION / ORTECH
TEST 8 120 min. BLANK CONDITIONING

PRODUCTS	WT	WT PERCENT	ASSAYS NI	CU	S	MINERAL ASSAYS PN	CP	PO	GN	PO/PN RATIO	%NI as NiS
CONC.1	4.47	4.47	2.15	0.74	32.60	4.59	2.15	76.21	17.06	16.62	2.66
CONC.2	7.16	7.16	4.53	2.80	31.10	11.41	8.12	61.53	18.94	5.39	6.20
CONC.3	12.31	12.31	1.23	0.27	31.80	2.03	0.78	77.53	19.66	38.28	1.55
TAILS.	76.06	76.06	0.83	0.05	19.70	1.44	0.15	48.17	50.24	33.46	1.67
CALC. HEAD	100.00	100.00	1.20	0.30	22.58	2.37	0.88	54.00	42.75	22.82	2.13

	DISTRIBUTION NI	CU	S	MINERAL DISTRIBUTION PN	CP	PO	GN
CONC.1	7.99	10.85	6.45	8.66	10.85	6.31	1.78
CONC.2	26.96	65.77	9.85	34.53	65.77	8.16	3.17
CONC.3	12.58	10.90	17.33	10.53	10.90	17.67	5.66
FIN.TAIL.	52.47	12.48	66.35	46.28	12.48	67.86	89.38
CALC.HEAD	100.00	100.00	100.00	100.00	100.00	100.00	100.00

CUMULATIVE PRODUCTS	WT	WT PERCENT	ASSAYS NI	CU	S	MINERAL ASSAYS PN	CP	PO	GN	PO/PN RATIO	%NI as NiS
CONC.1	4.47	4.47	2.15	0.74	32.60	4.59	2.15	76.21	17.06	16.62	2.66
CONC.1+2	11.63	11.63	3.62	2.01	31.68	8.79	5.82	67.17	18.22	7.64	4.75
CONC.1TO3	23.94	23.94	2.39	1.11	31.74	5.31	3.23	72.50	18.96	13.65	3.07
TAILS.	76.06	76.06	0.83	0.05	19.70	1.44	0.15	48.17	50.24	33.46	1.67
CALC. HEAD	100.00	100.00	1.20	0.30	22.58	2.37	0.88	54.00	42.75	22.82	2.13

	DISTRIBUTION NI	CU	S	MINERAL DISTRIBUTION PN	CP	PO	GN
CONC.1	7.99	10.85	6.45	8.66	10.85	6.31	1.78
CONC.1+2	34.95	76.62	16.31	43.19	76.62	14.47	4.96
CONC.1TO3	47.53	87.52	33.65	53.72	87.52	32.14	10.62
TAILS.	52.47	12.48	66.35	46.28	12.48	67.86	89.38
CALC.HEAD	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 26

Flotation Characteristics

Test 1: pH 8.0 - pH 8.6 (Table 18)

Test 2: 8 mL DF250 added instead of 2 mL (Table 20)
heavy froth occurances

Test 3: 2 mL DF250 added as required (Table 21)

Test 4: Repeat test 1 (Table 19)

Test 5: (Table 22)

Starting pH	8.8
10 Min.	7.8
20 Min.	7.7
40 Min.	7.6
60 Min.	7.6
end	7.7

Test 6: .10% H_2SO_4 used in acid conditioning (Table 23)

Initial pH	8.8
add 50 mL H_2SO_4	pH 4.0
5 Min.	pH 6.4
add T. ferrooxidans	pH 5.0 (after 20 minutes)
add flotation reagents	pH 4.8

Observe voluminous float.

Test 7:

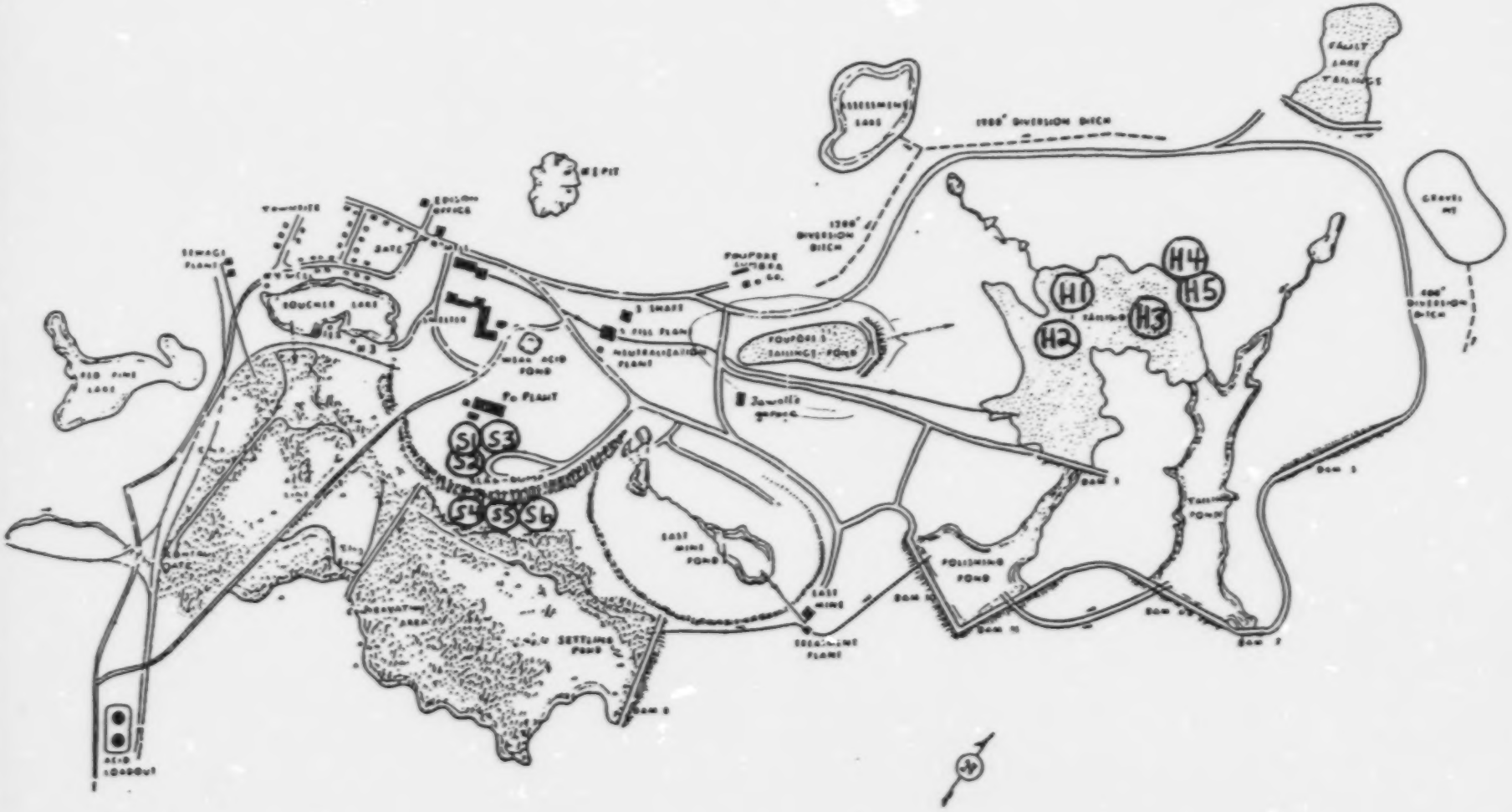
Initial pH:	7.5	60 Min.	pH 7.5
0 Min.	pH 8.7	90 Min.	pH 7.5
5 Min.	pH 8.1	120 Min.	pH 7.6
15 Min.	pH 8.0	Reagent addition	pH 7.6
30 Min.	pH 7.7	Pulp Temp.	43°C

Test 8:

Initial pH	8.8	90 Min.	pH 7.5
5 Min.	pH 8.4	120 Min.	pH 7.5
15 Min.	pH 8.0	Reagent addition	pH 7.6
30 Min.	pH 7.9	Pulp Temp.	43°C
60 Min.	pH 7.5		

APPENDIX I: Figures 1 to 36

FIGURE 1 SAMPLING LOCATIONS



alconbridge area effluent treatment system.

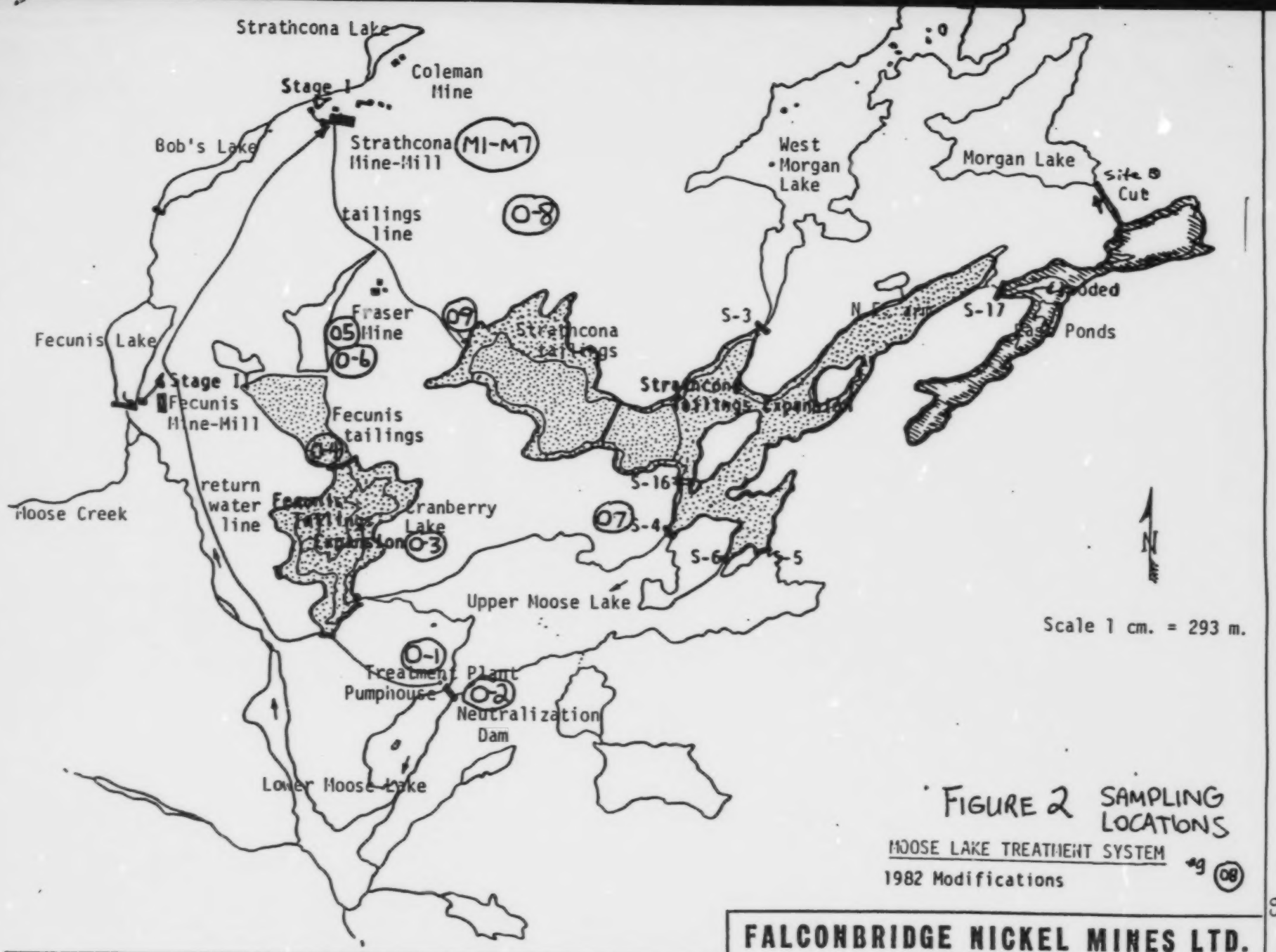


FIGURE 2 SAMPLING LOCATIONS

MOOSE LAKE TREATMENT SYSTEM

1982 Modifications

O8

FALCONBRIDGE NICKEL MINES LTD.

FALCONBRIDGE, ONTARIO R.E.M. 1982

FIGURE 3 SAMPLING LOCATIONS

eg. (01)

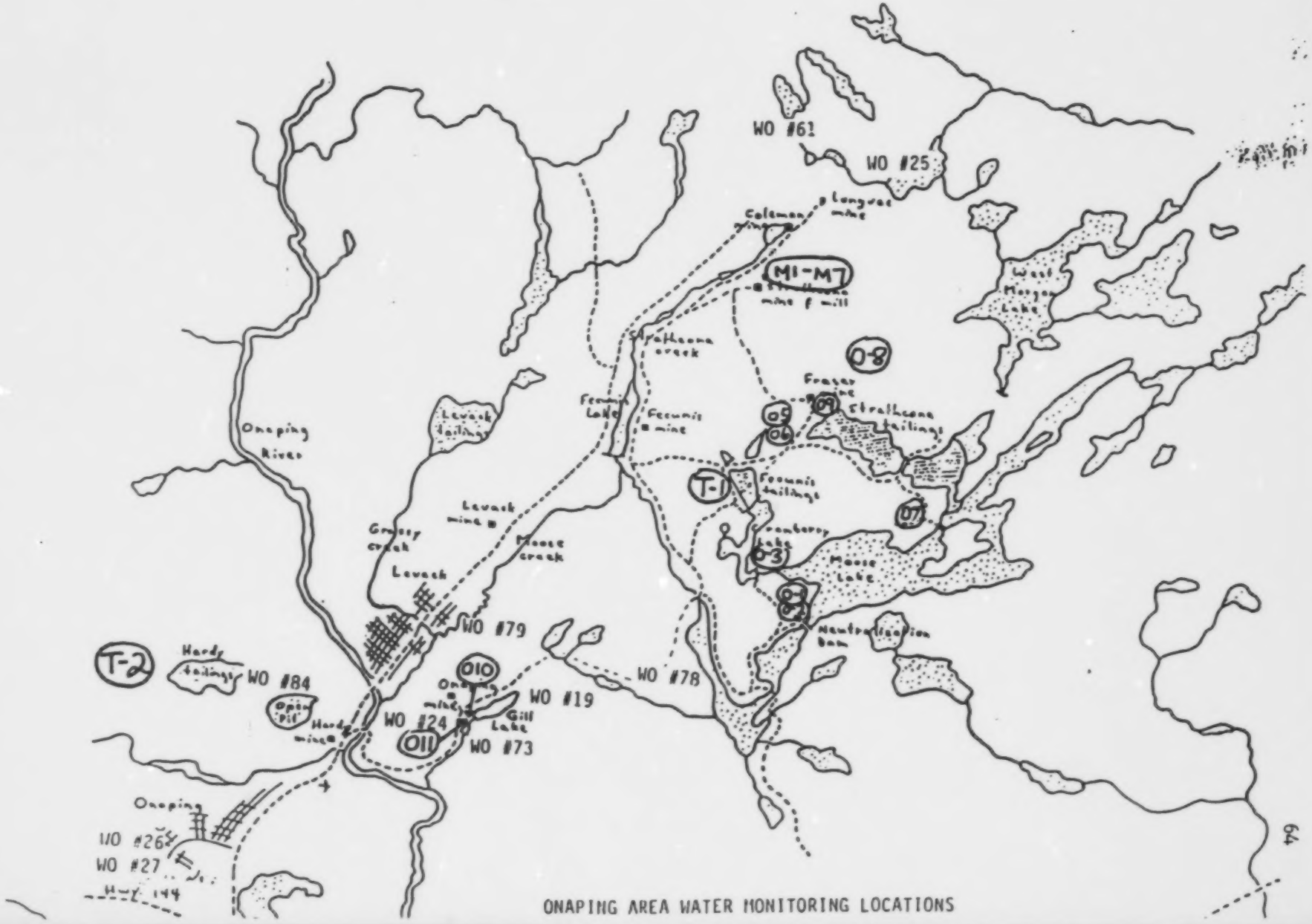


Figure 4
Bioleaching of Pyrrhotite tailings by Thiobacillus ferrooxidans (SM-4)

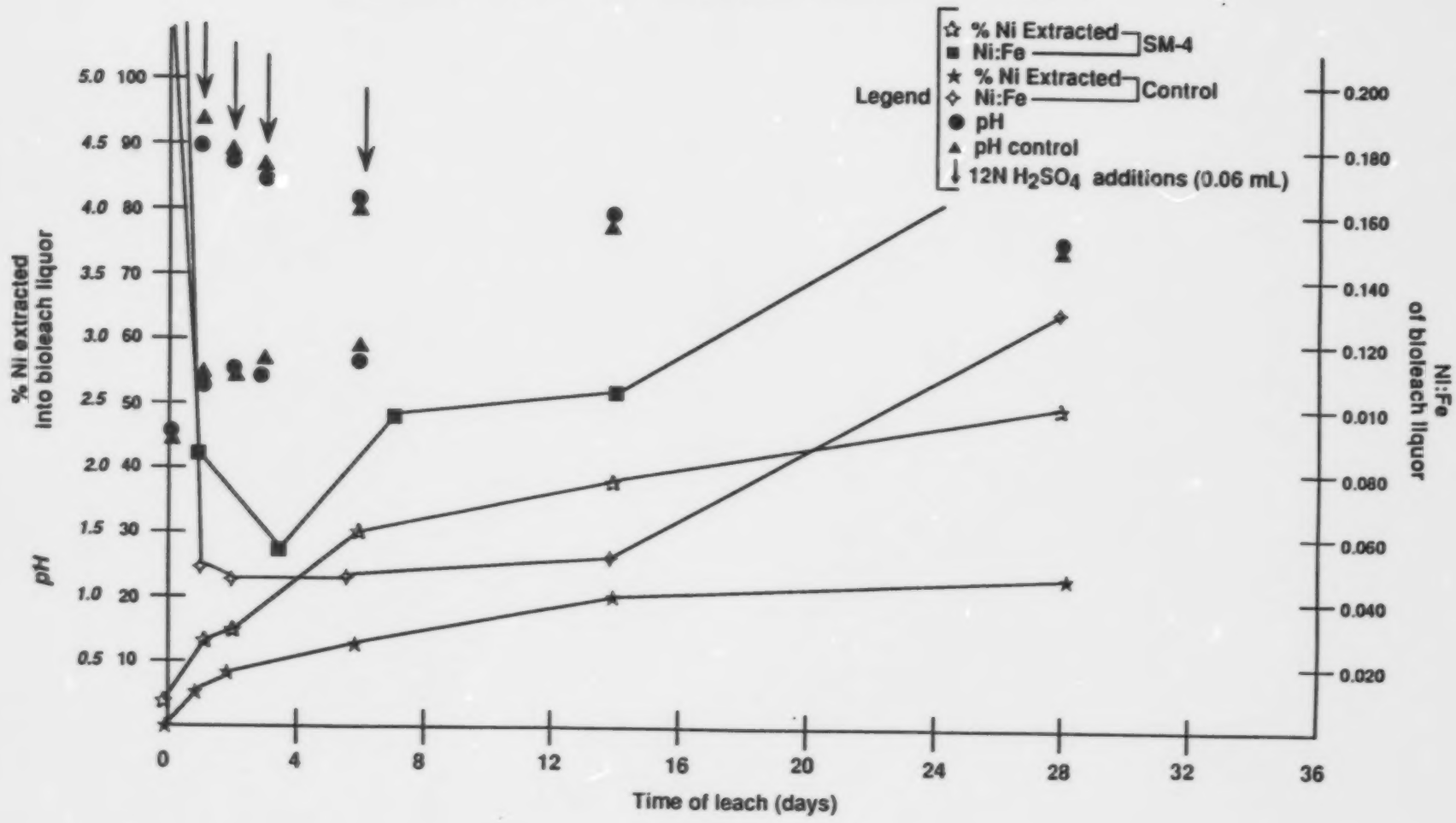


Figure 5
Bioleaching of Pyrrhotite tailings by Thiobacillus ferrooxidans (fecunis)

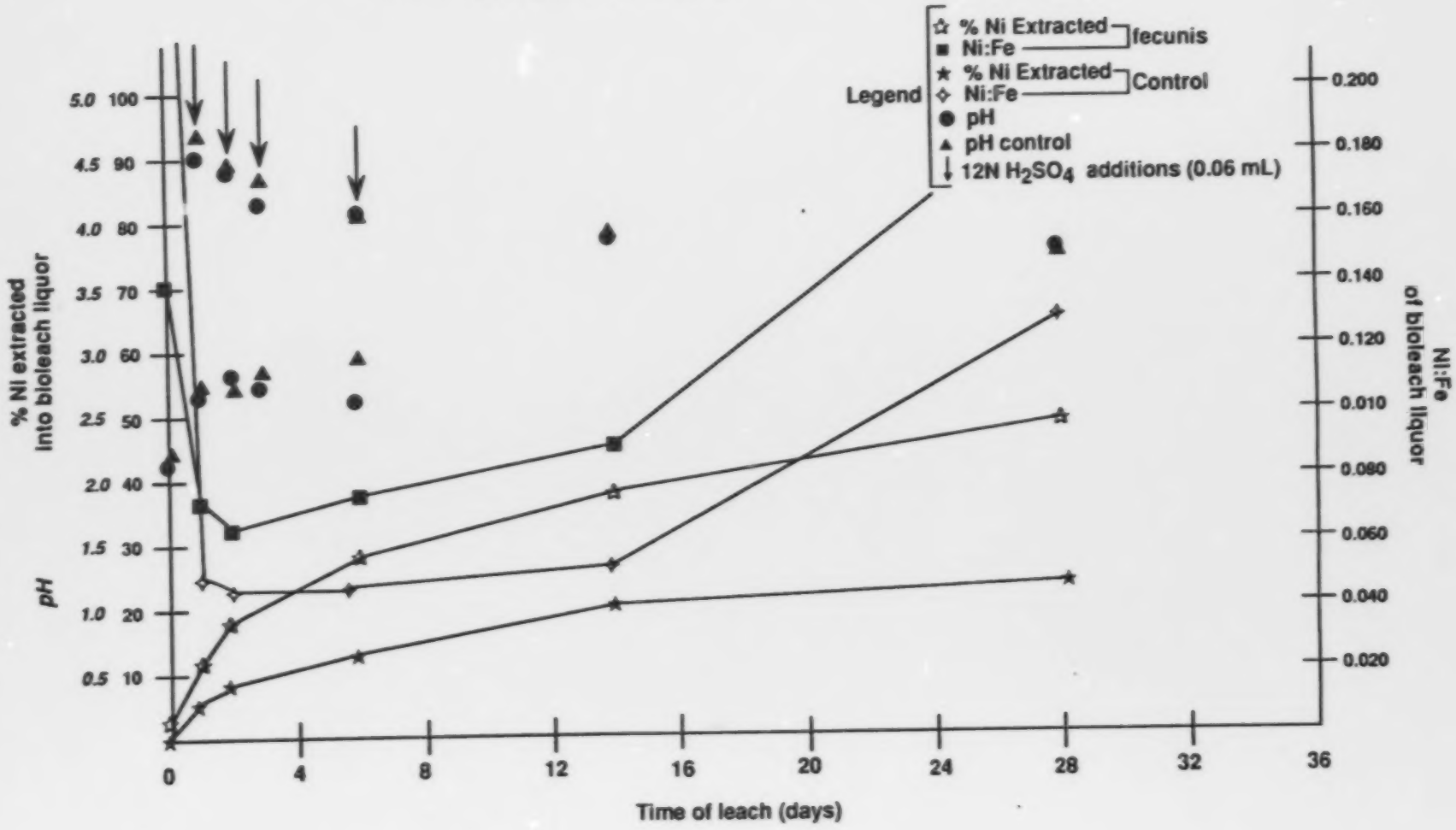


Figure 6
Bioleaching of Pyrrhotite tailings by Thiobacillus ferrooxidans (O-3)

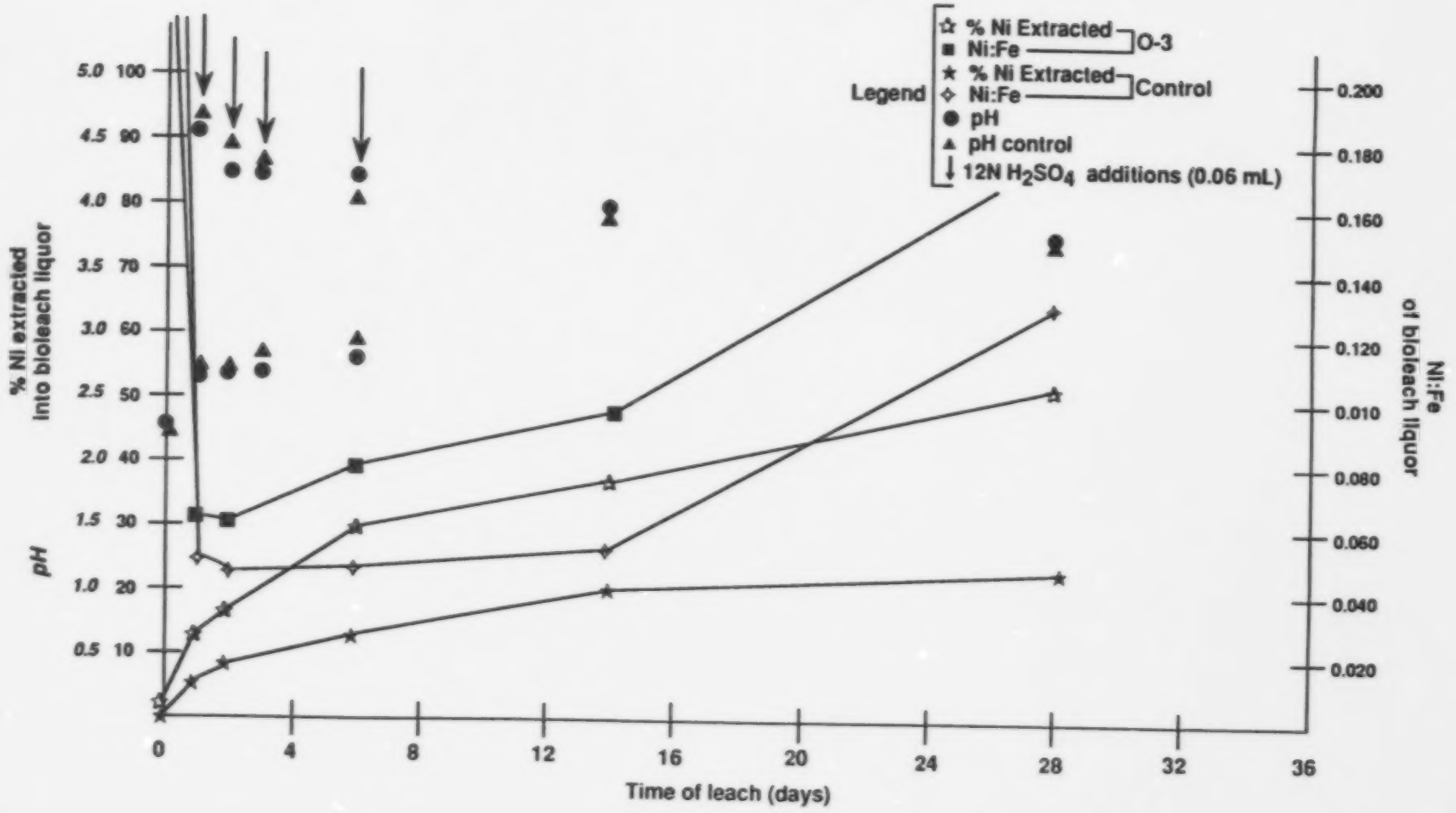


Figure 7
Bioleaching of Pyrrhotite tailings by Thiobacillus ferrooxidans
and Thiobacillus thiooxidans (SM-4)

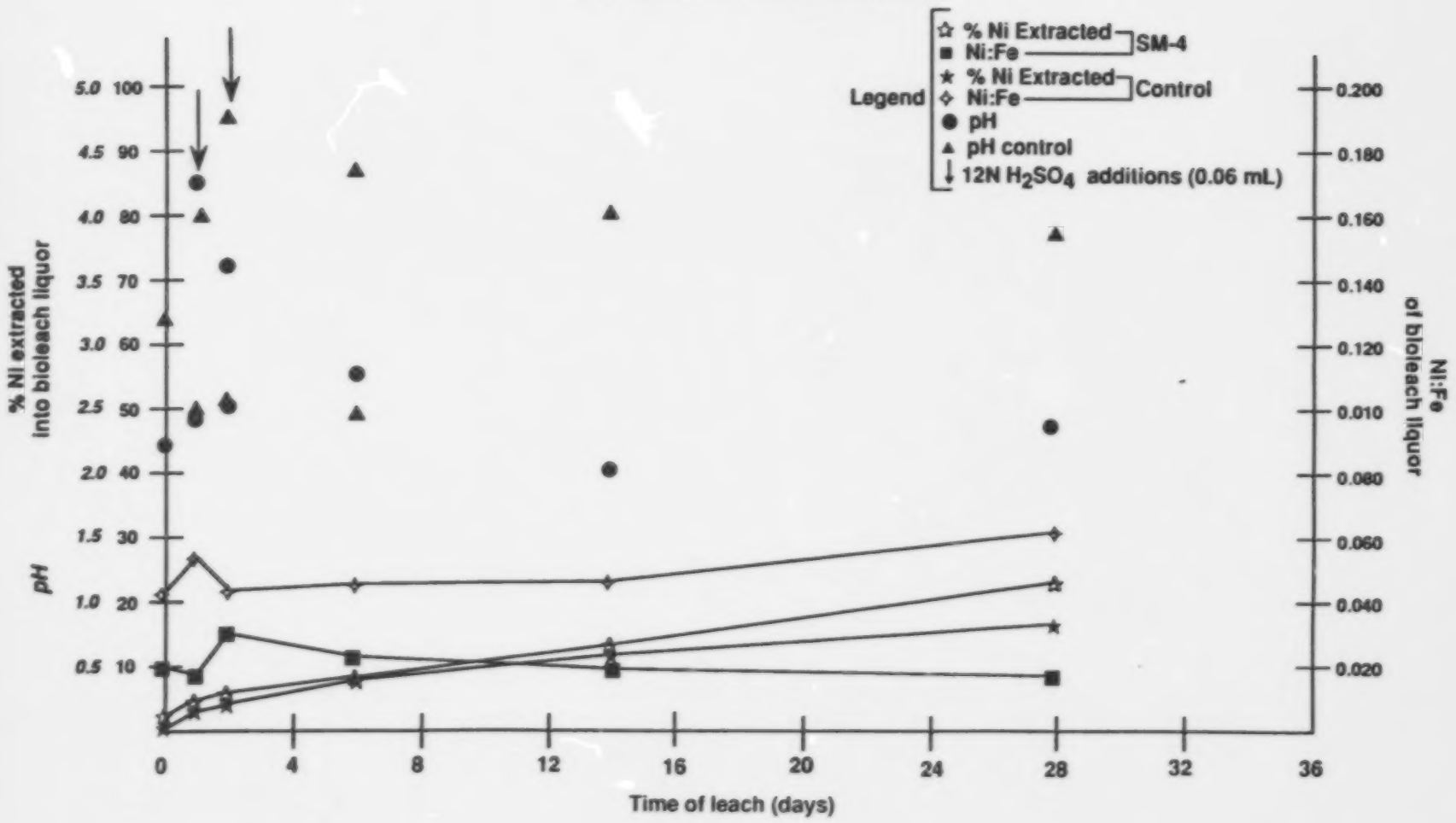


Figure 8
Bioleaching of Pyrrhotite tailings by Thiobacillus ferrooxidans and Thiobacillus thiooxidans (fecunis)

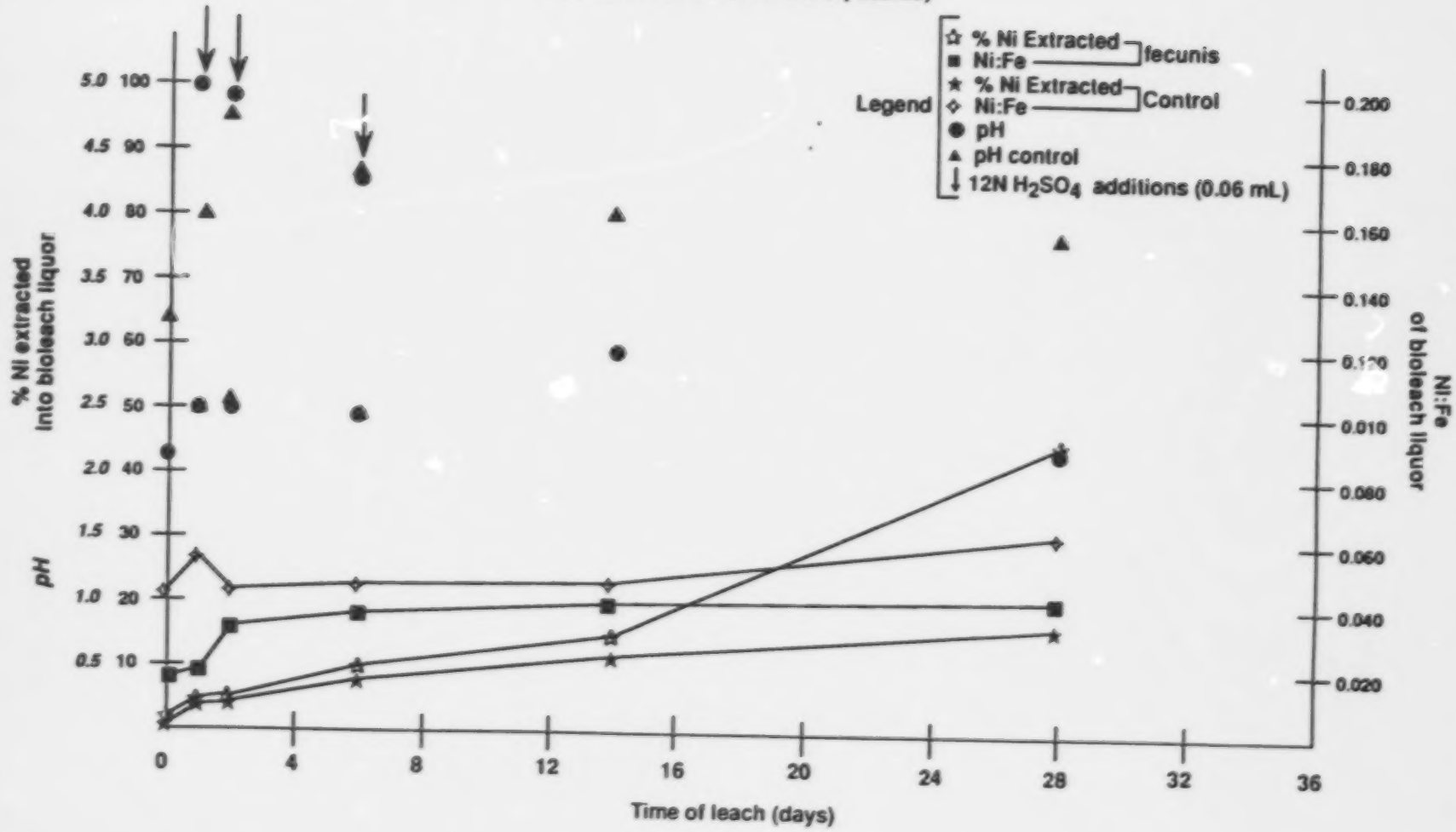


Figure 9
Bioleaching of Pyrrhotite tailings by Thiobacillus ferrooxidans
and Thiobacillus thiooxidans (0-3)

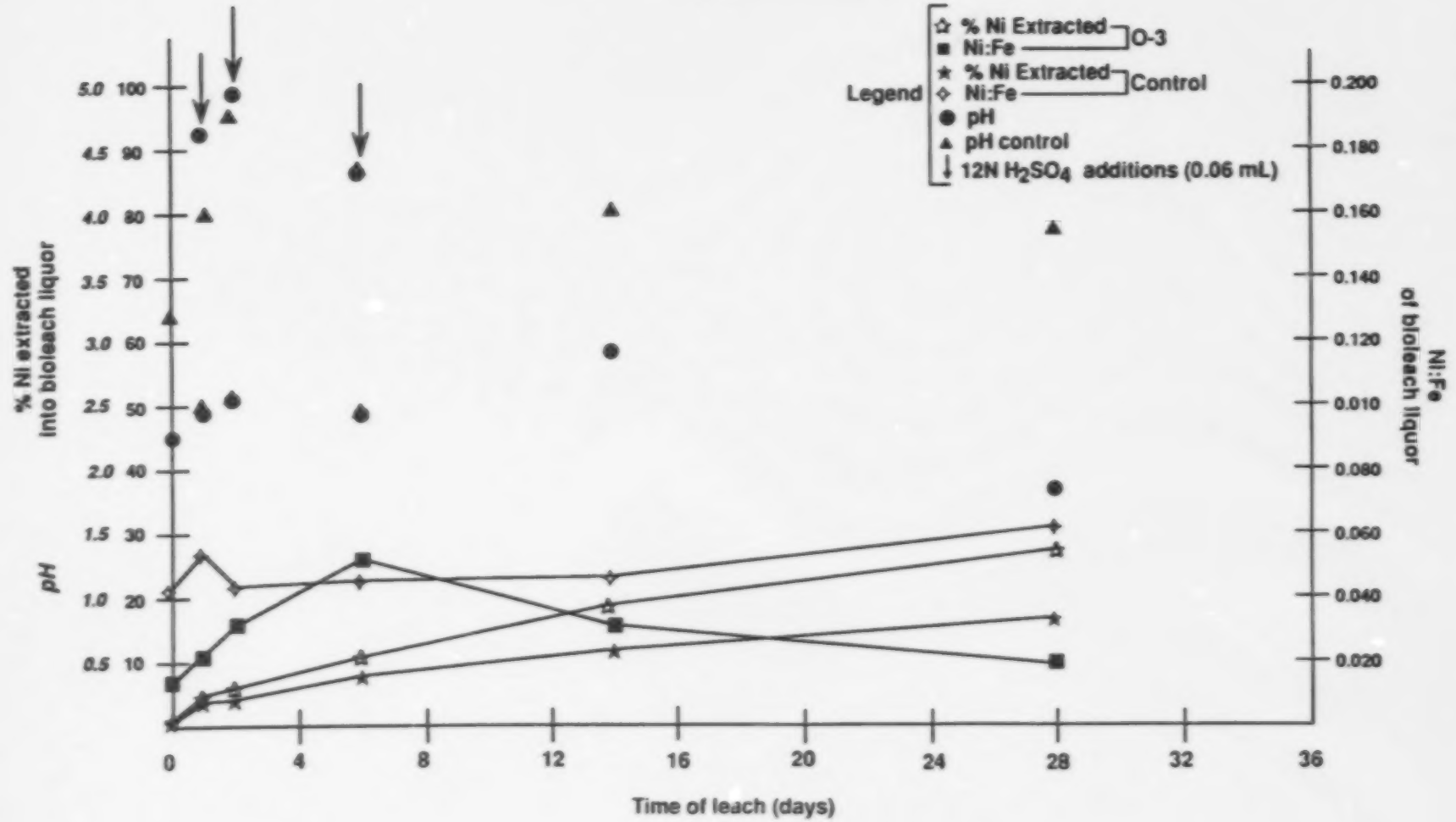


Figure 10
Bioleaching of Pyrrhotite tailings by Thiobacillus ferrooxidans
and Thiobacillus thiooxidans (0-9)

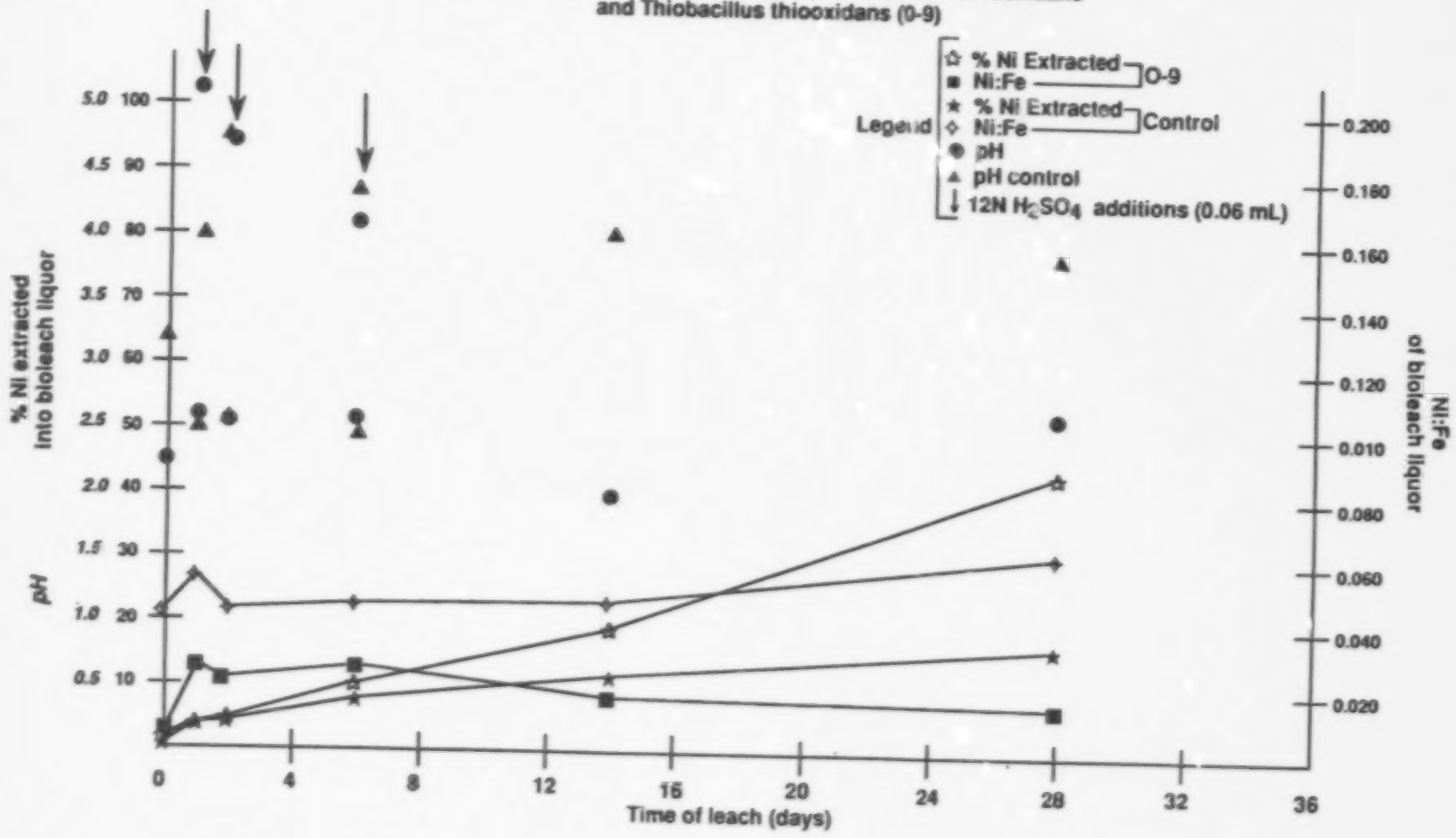


Figure 11

Bioleaching of PO Tails by T. ferrooxidans and T. thiooxidans with 60 ppm Cu Present

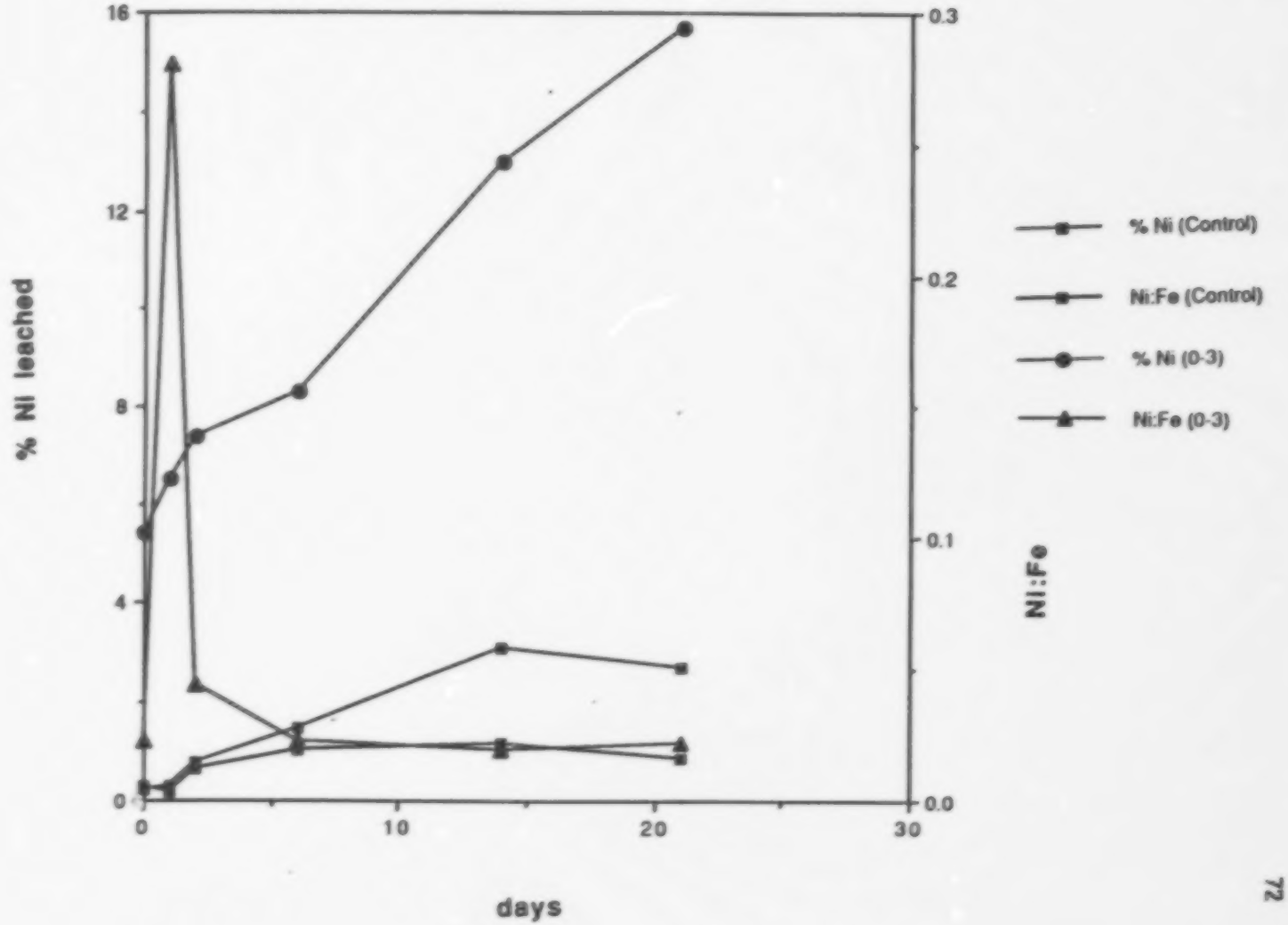


Figure 12

Bioleaching of PO Tails by T. ferrooxidans and T. thiooxidans wit 120 ppm Cu Present

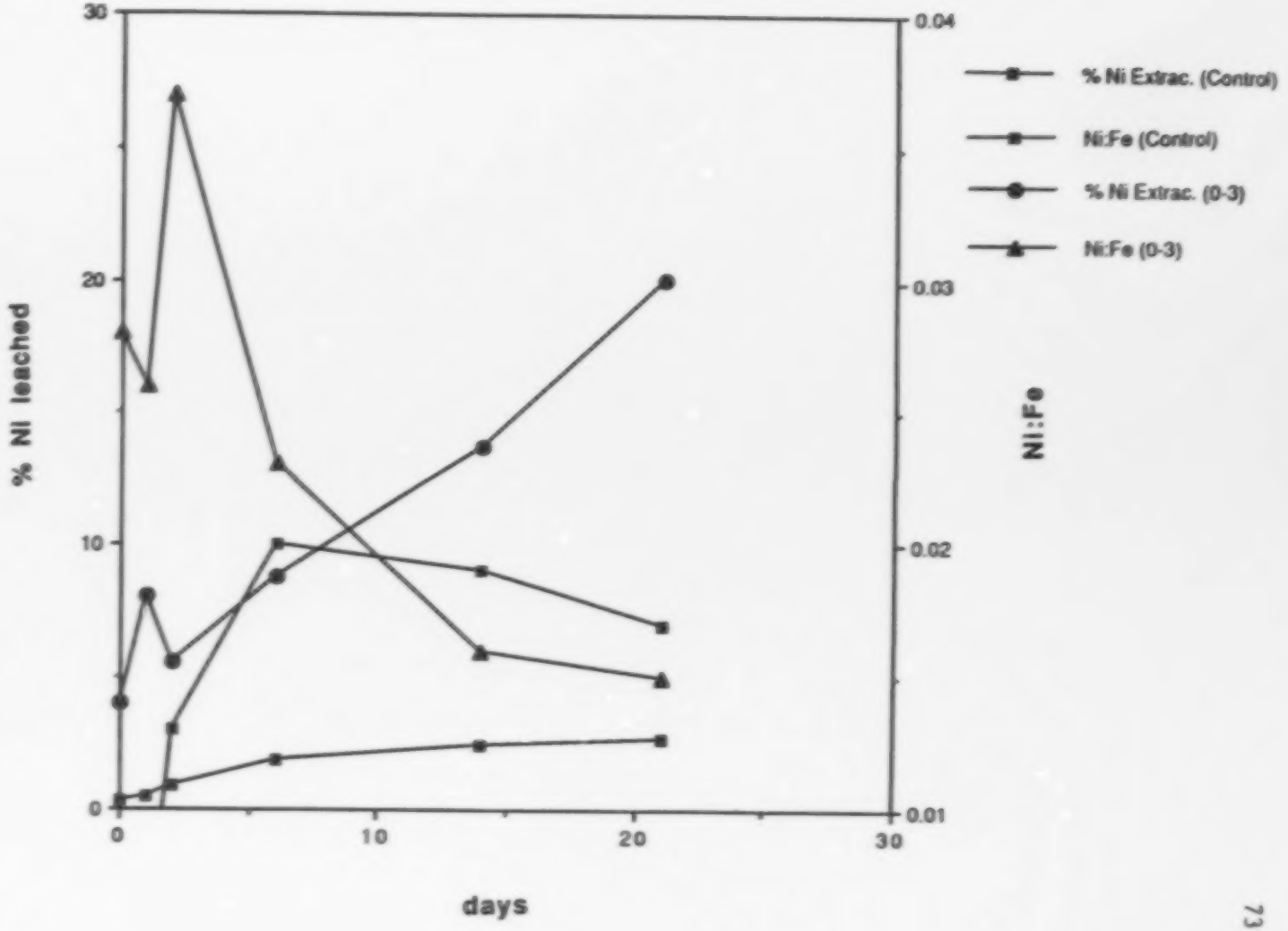


Figure 13

Bioleaching of PO Tails by *T. ferrooxidans* and *T. thiooxidans* in Low Pulp Density

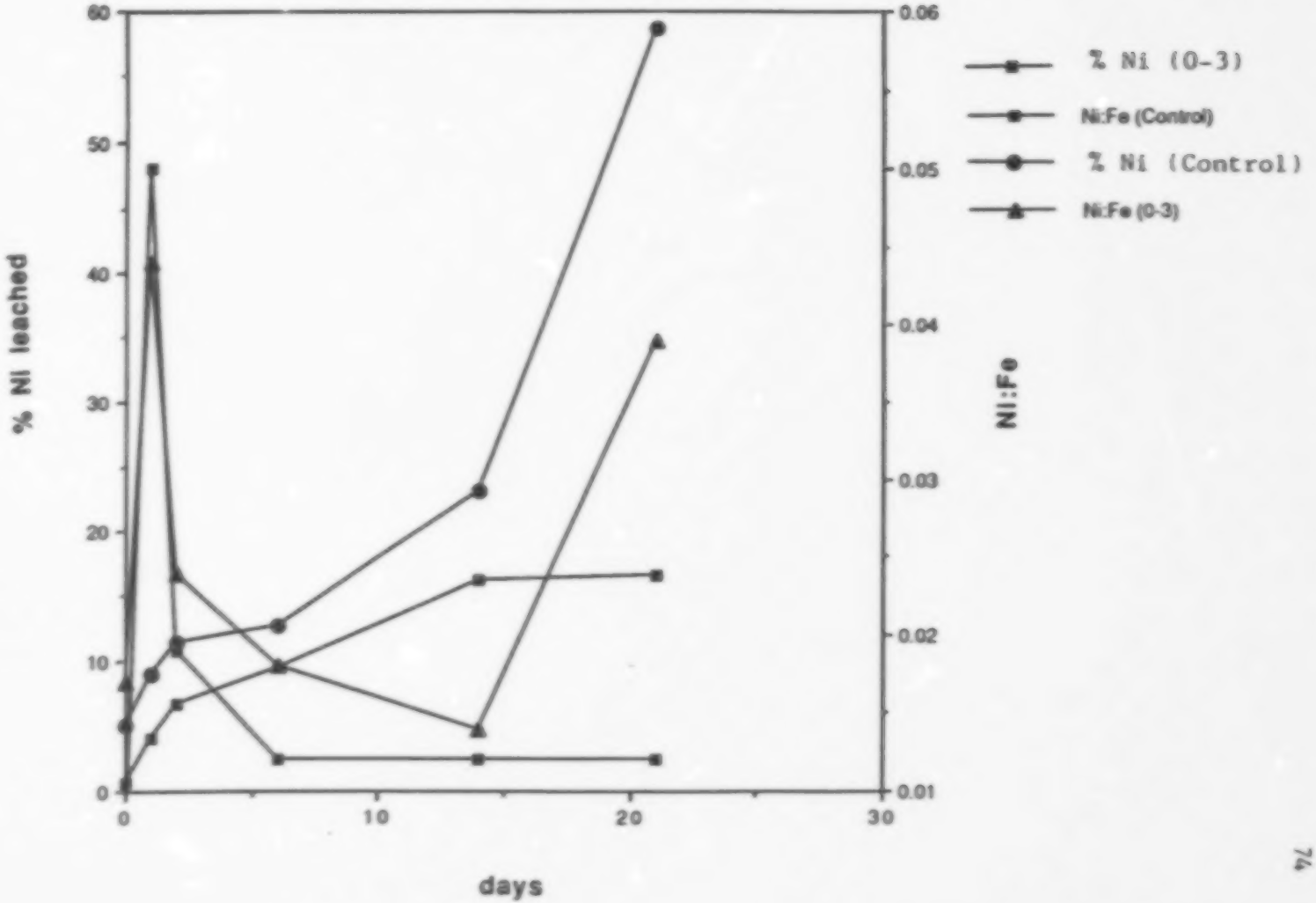


Figure 14

Bioleaching of PO Tails by I. ferrooxidans and I. thiooxidans in Moderate Pulp Density

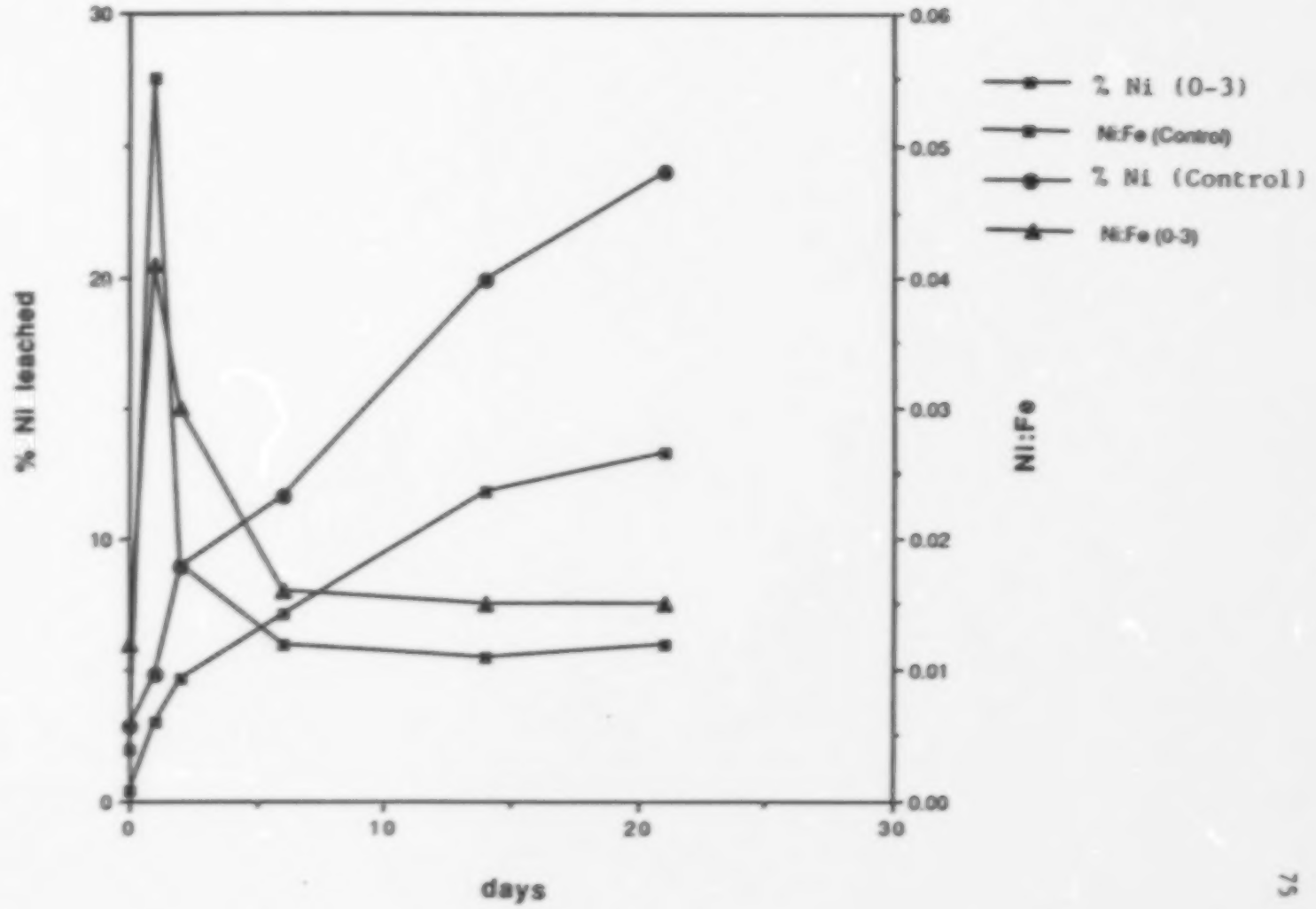
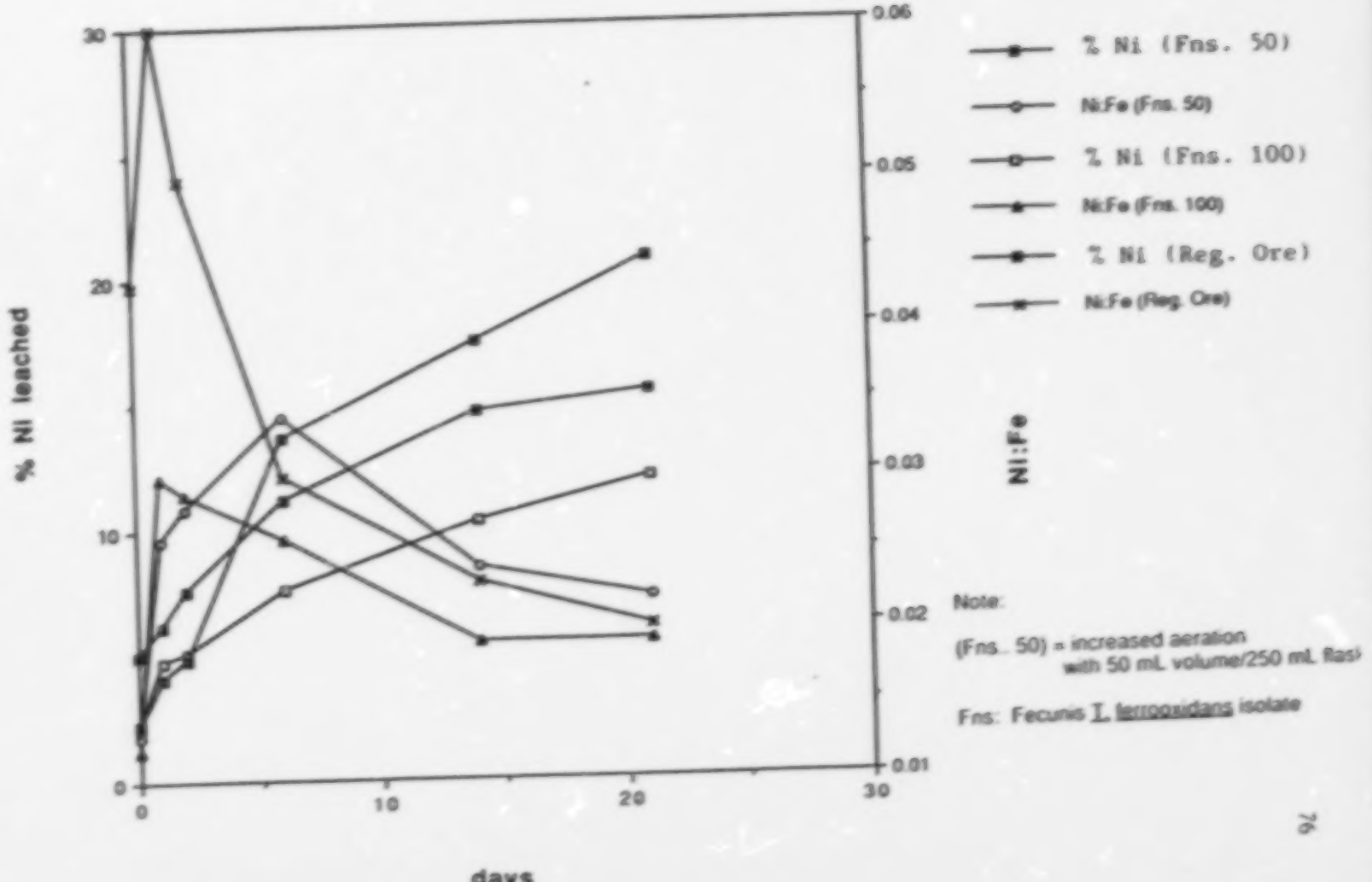


Figure 15

Bioleaching of PO Tails Using *I. ferrooxidans* and *I. thiooxidans* Under Increased Aeration and 60 ppm Cu



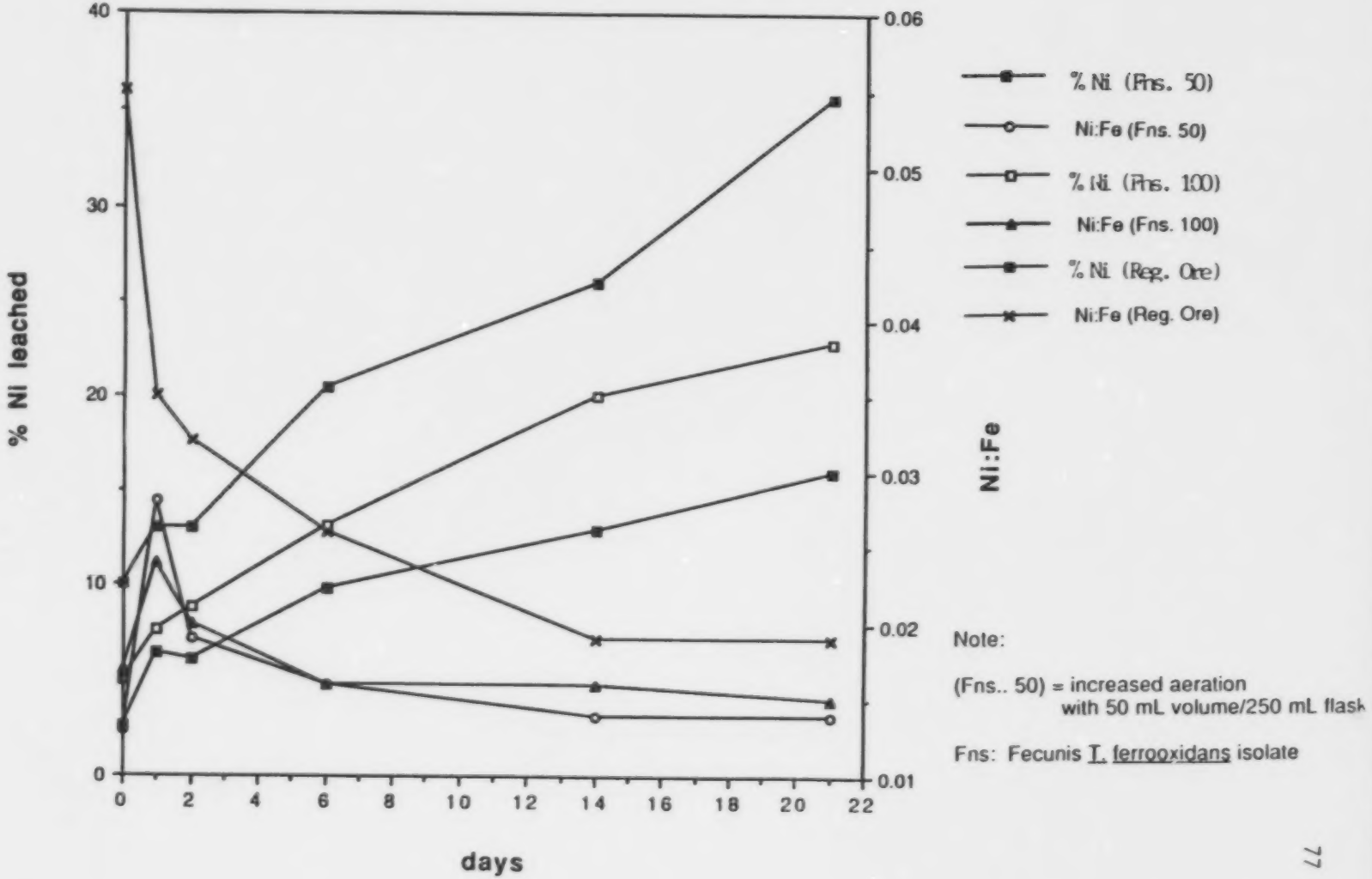
Note:

(Fns. 50) = increased aeration with 50 mL volume/250 mL flask

Fns: Fecunis *I. ferrooxidans* isolate

Figure 16

Bioleaching of PO Tails Using T. ferrooxidans and T. thiooxidans Under Increased Aeration and Low Pulp Density



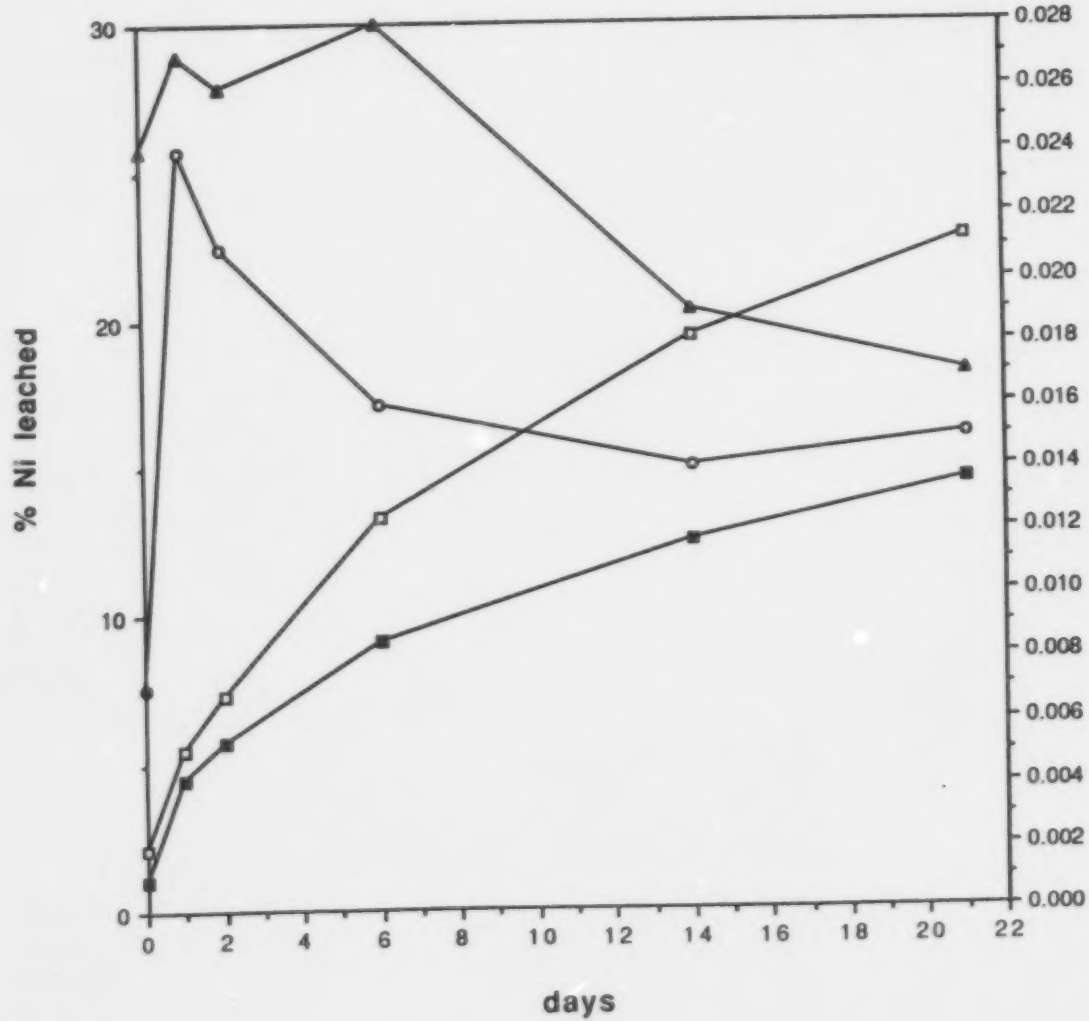
Note:

(Fns.. 50) = increased aeration with 50 mL volume/250 mL flask

Fns: Fecunis T. ferrooxidans isolate

Figure 17

Bioleaching of PO Tails Using *T. ferrooxidans* and *T. thiooxidans* Under Increased Aeration and Moderate Pulp Density



Note:

(Fns.. 50) = increased aeration

Fns: Fecunis *T. ferrooxidans* isolate

Figure 18

Untreated Ore, 20% p.d., 60 ppm Cu

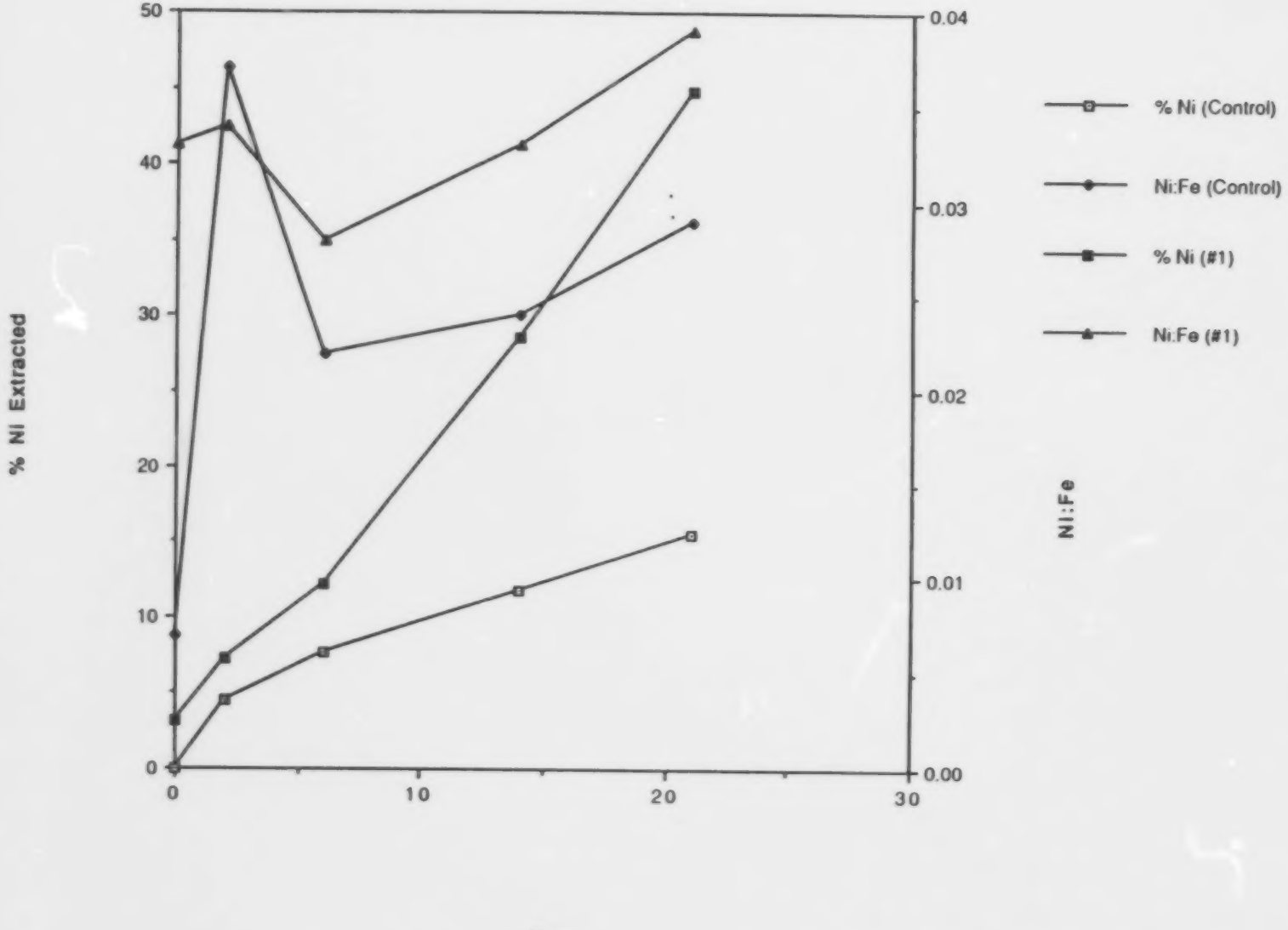


Figure 19

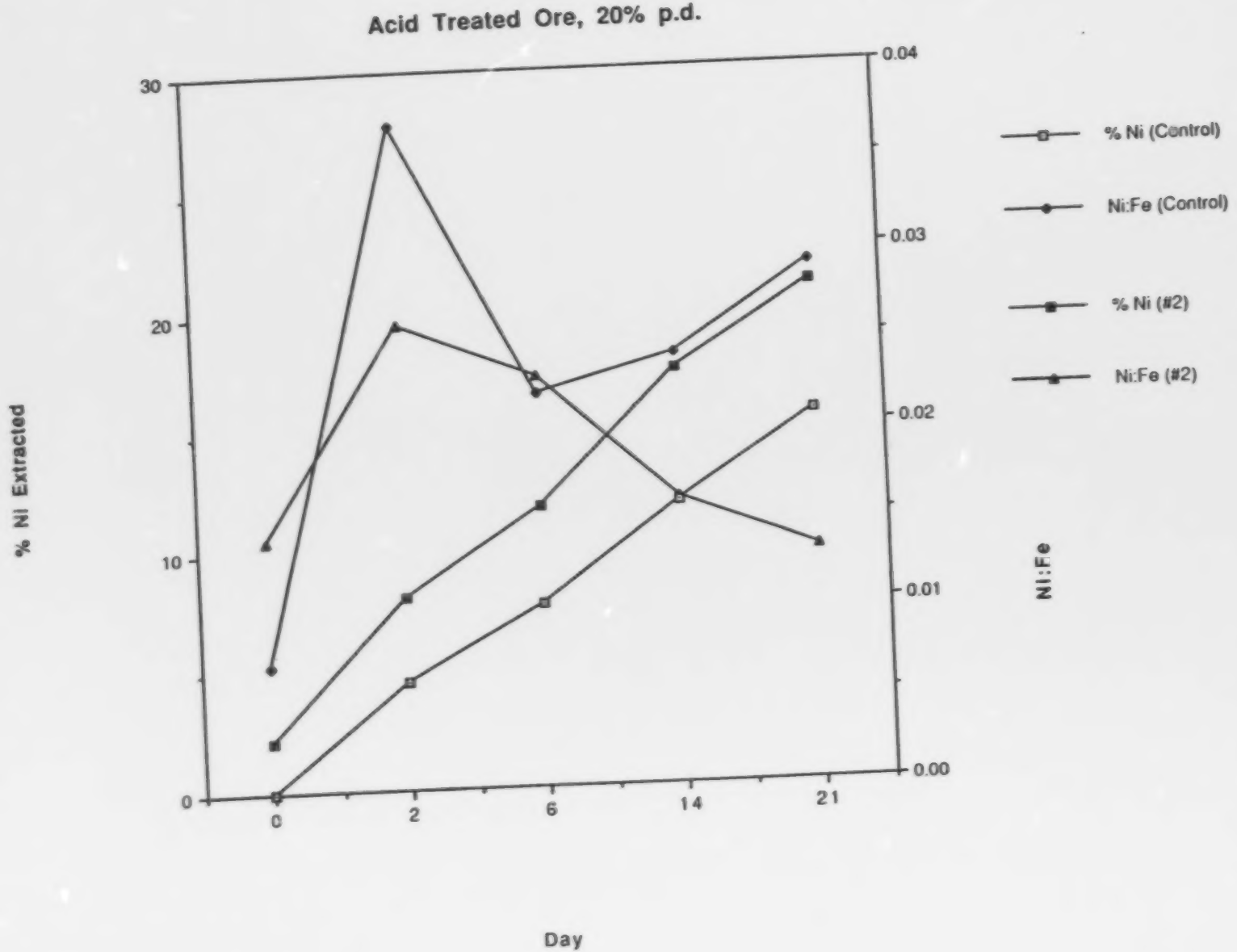

Acid Treated Ore, 20% p.d.
% Ni Extracted
Ni:Fe
Day
30
20
10
0
0.04
0.03
0.02
0.01
0.00
0
2
6
14
21
% Ni (Control)
Ni:Fe (Control)
% Ni (#2)
Ni:Fe (#2)

Figure 20

Acid Treated Ore, 20% p.d., 60 ppm Cu

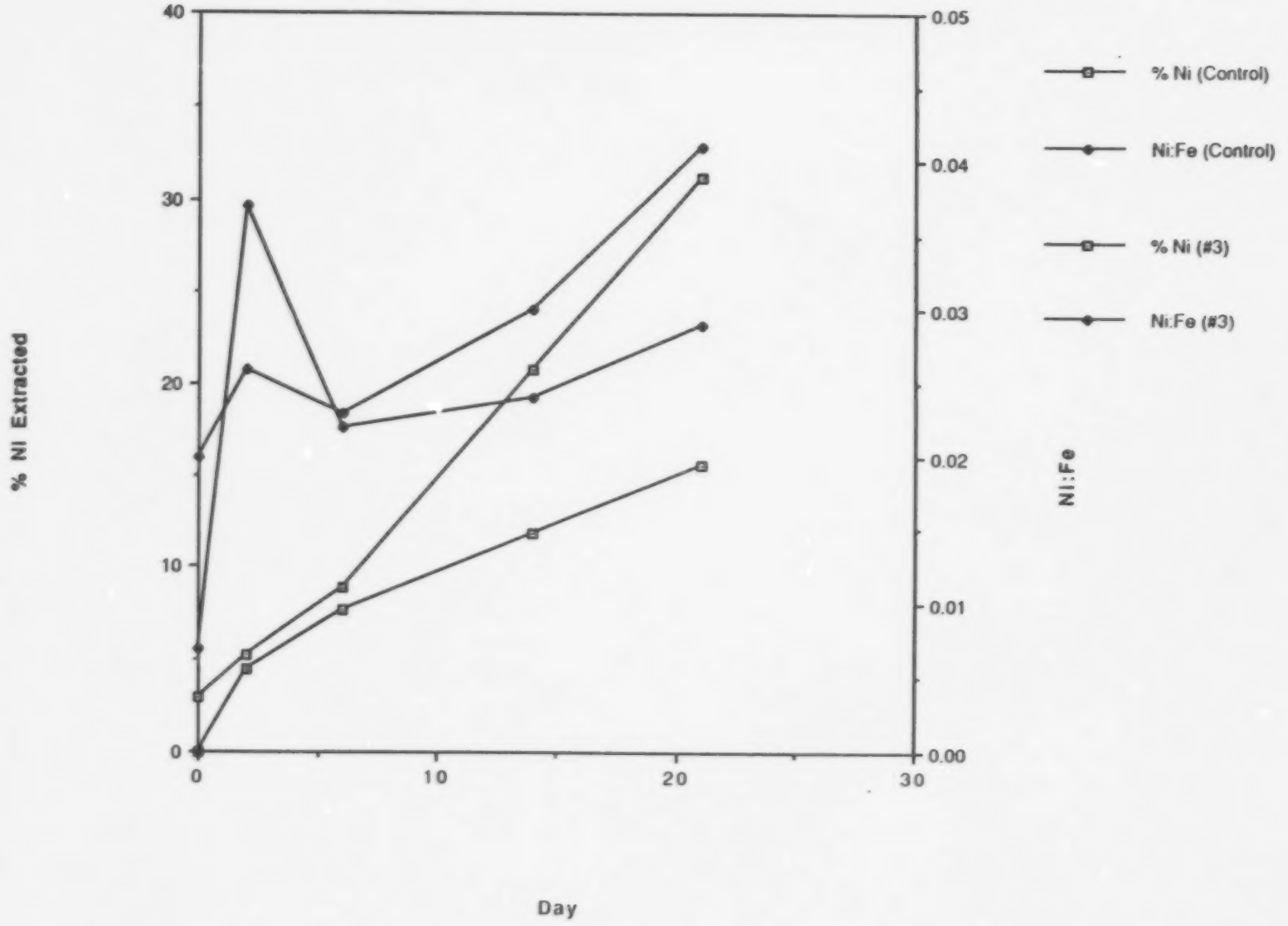


Figure 21

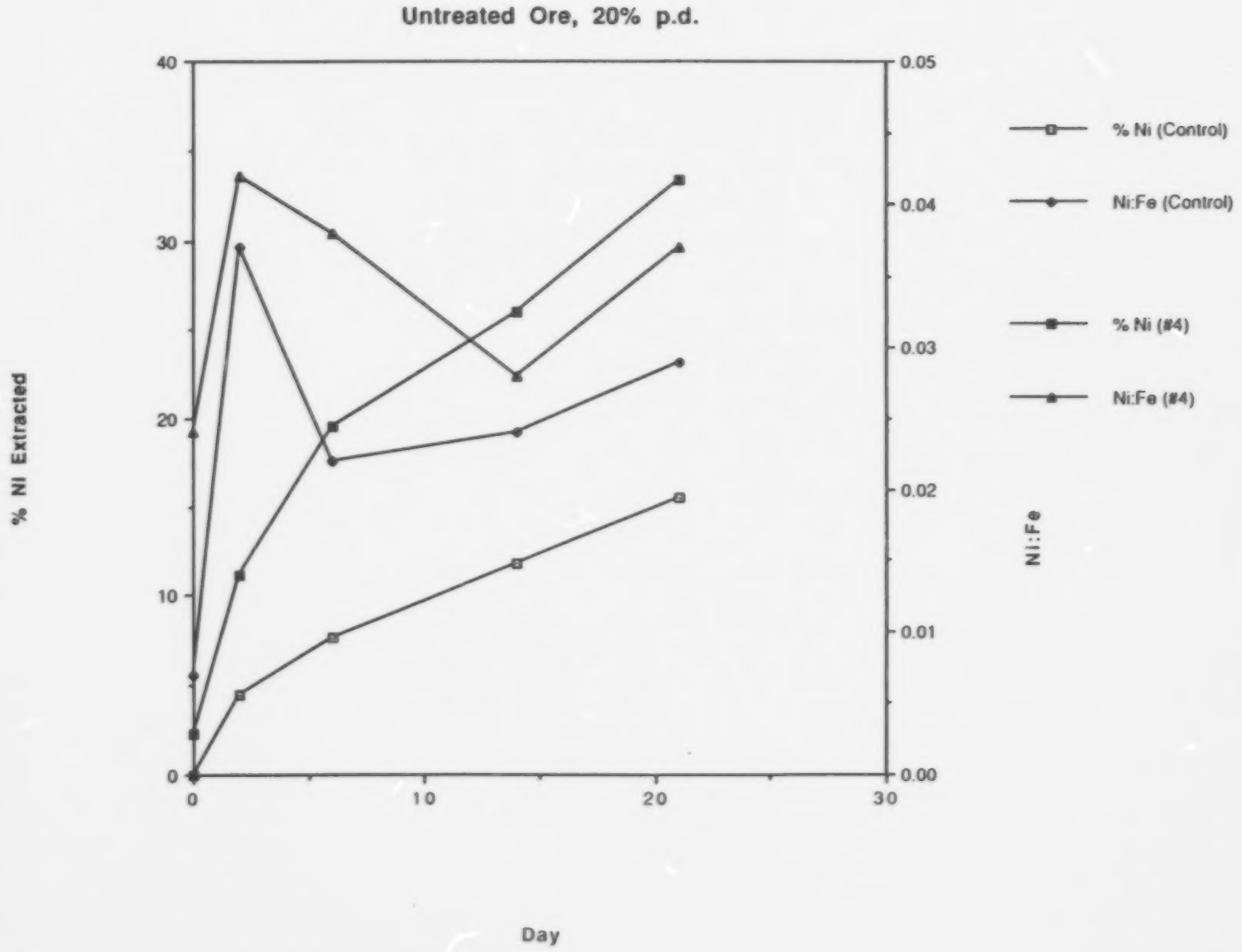

Untreated Ore, 20% p.d.
% Ni Extracted
Ni:Fe
Day
0
10
20
30
40
0.00
0.01
0.02
0.03
0.04
0.05
% Ni (Control)
Ni:Fe (Control)
% Ni (#4)
Ni:Fe (#4)

Figure 22

Effect of 20 Min. Bioconditioning on Ni Flotation Products

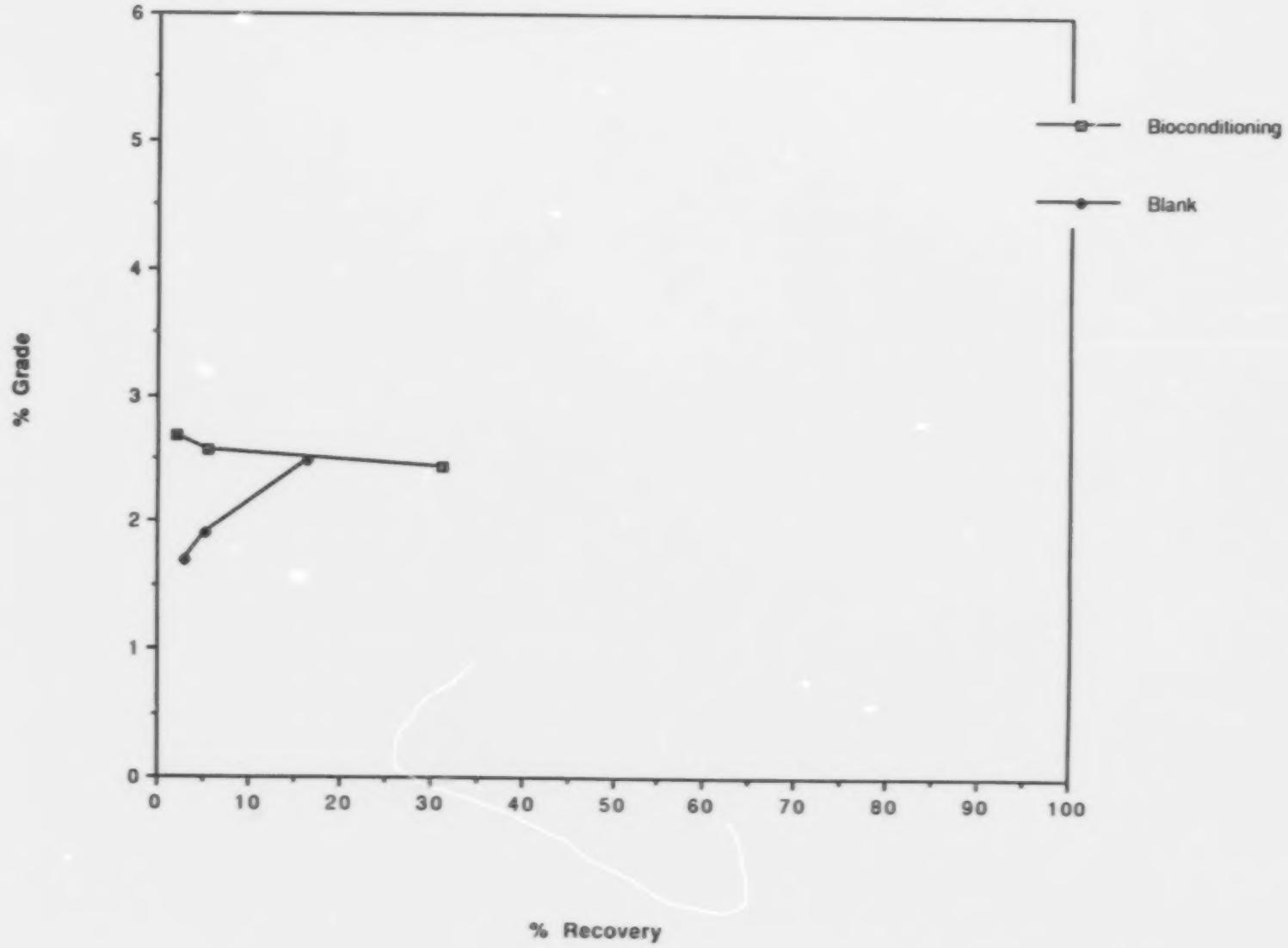


Figure 23

Effect of 20 Min. Bioconditioning on Cu Flotation Products

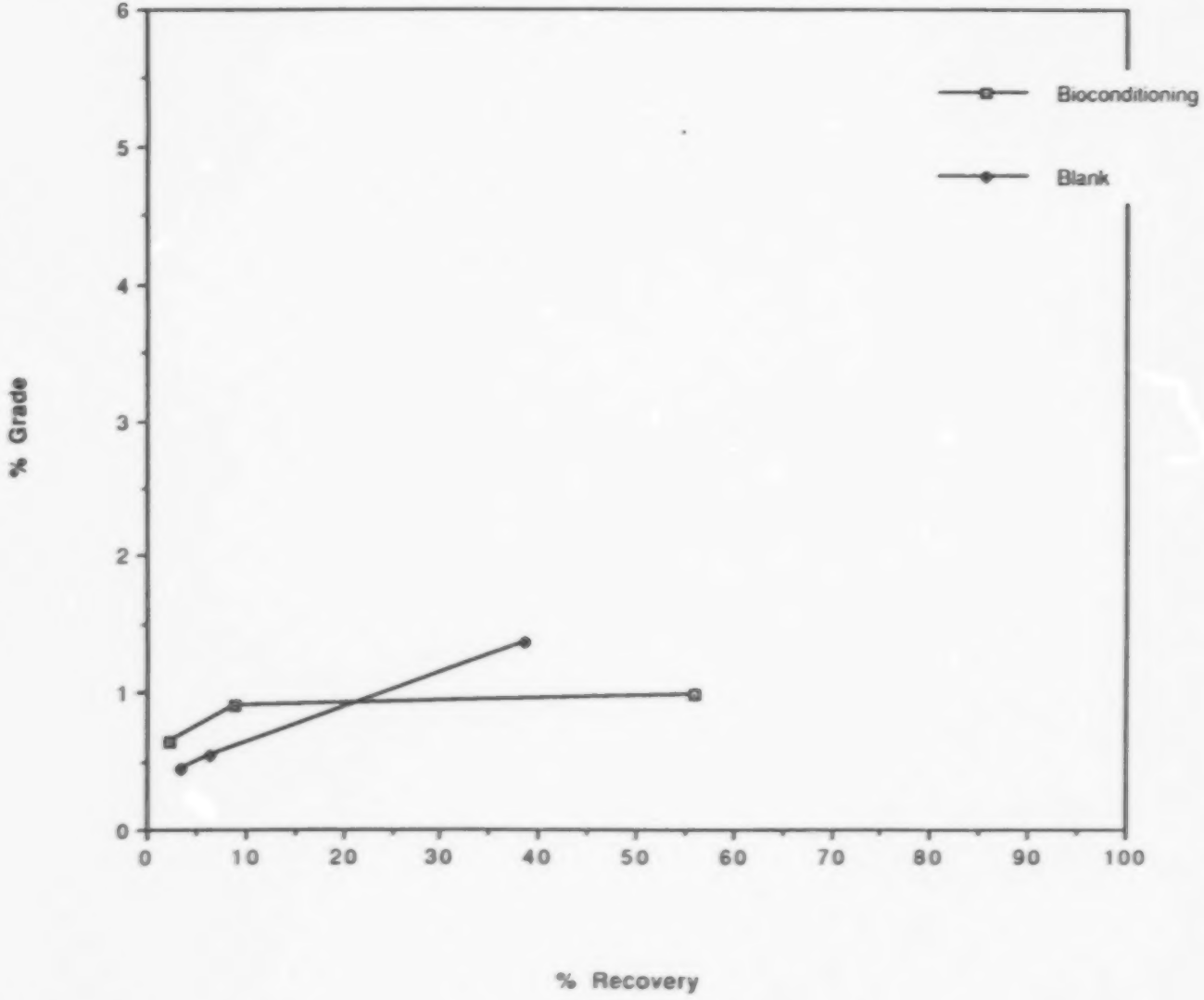


Figure 24

Effect of 20 Min. Bioconditioning on

Pentlandite Vs. Pyrrhotite Recovery

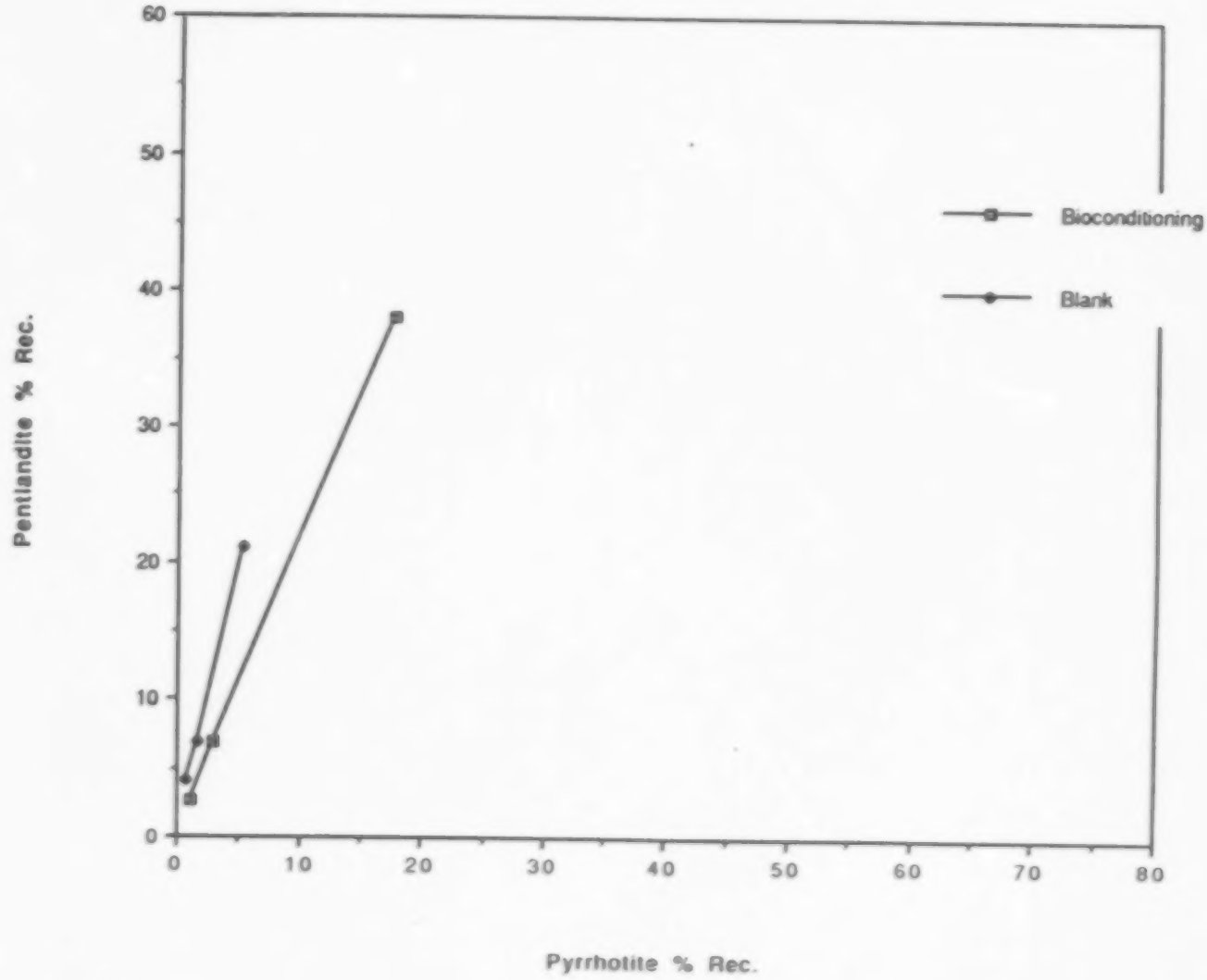


Figure 25

Effect of Time of Bioconditioning on

Ni Flotation Products

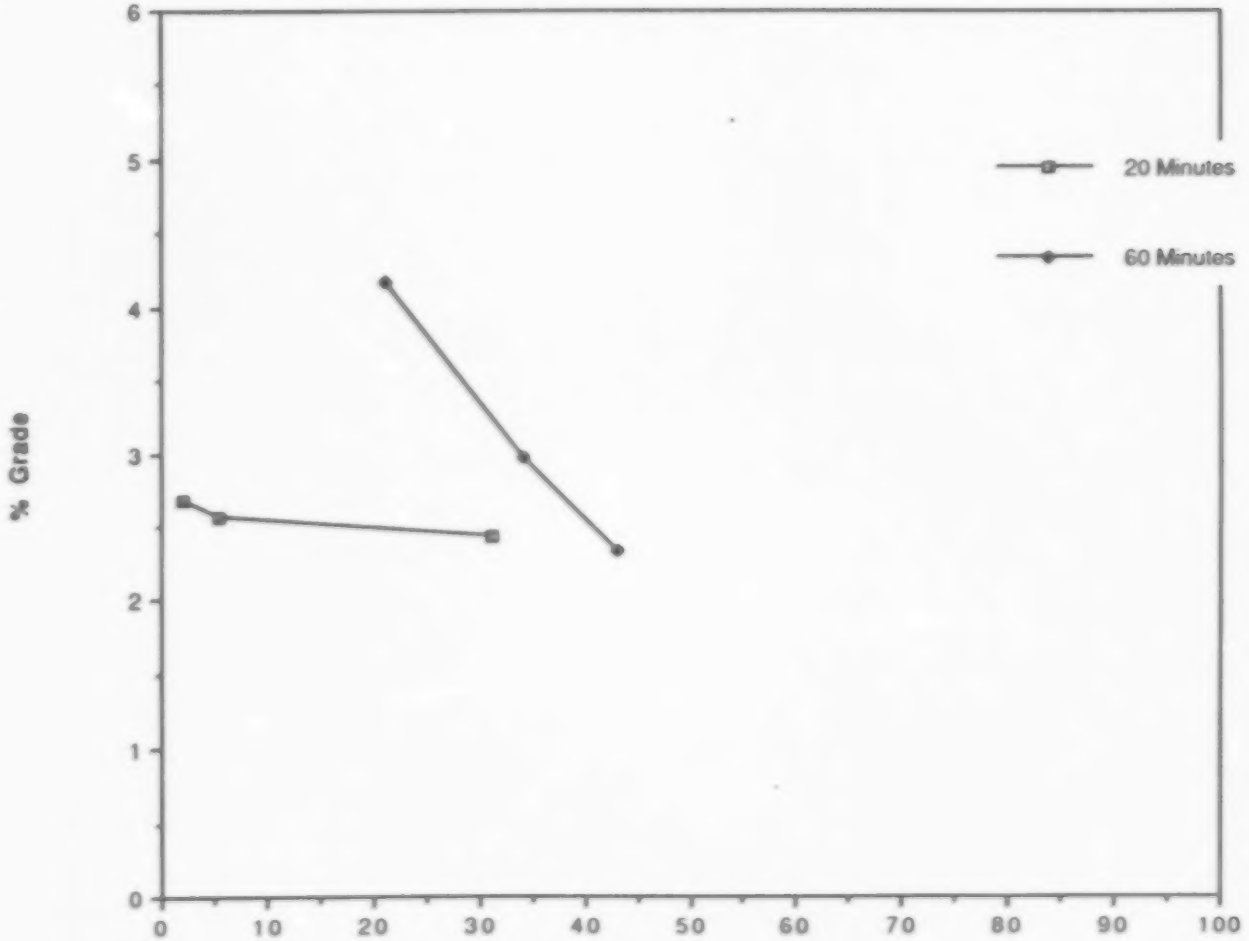


Figure 26

Effect of Time of Bioconditioning on

Cu Flotation Products

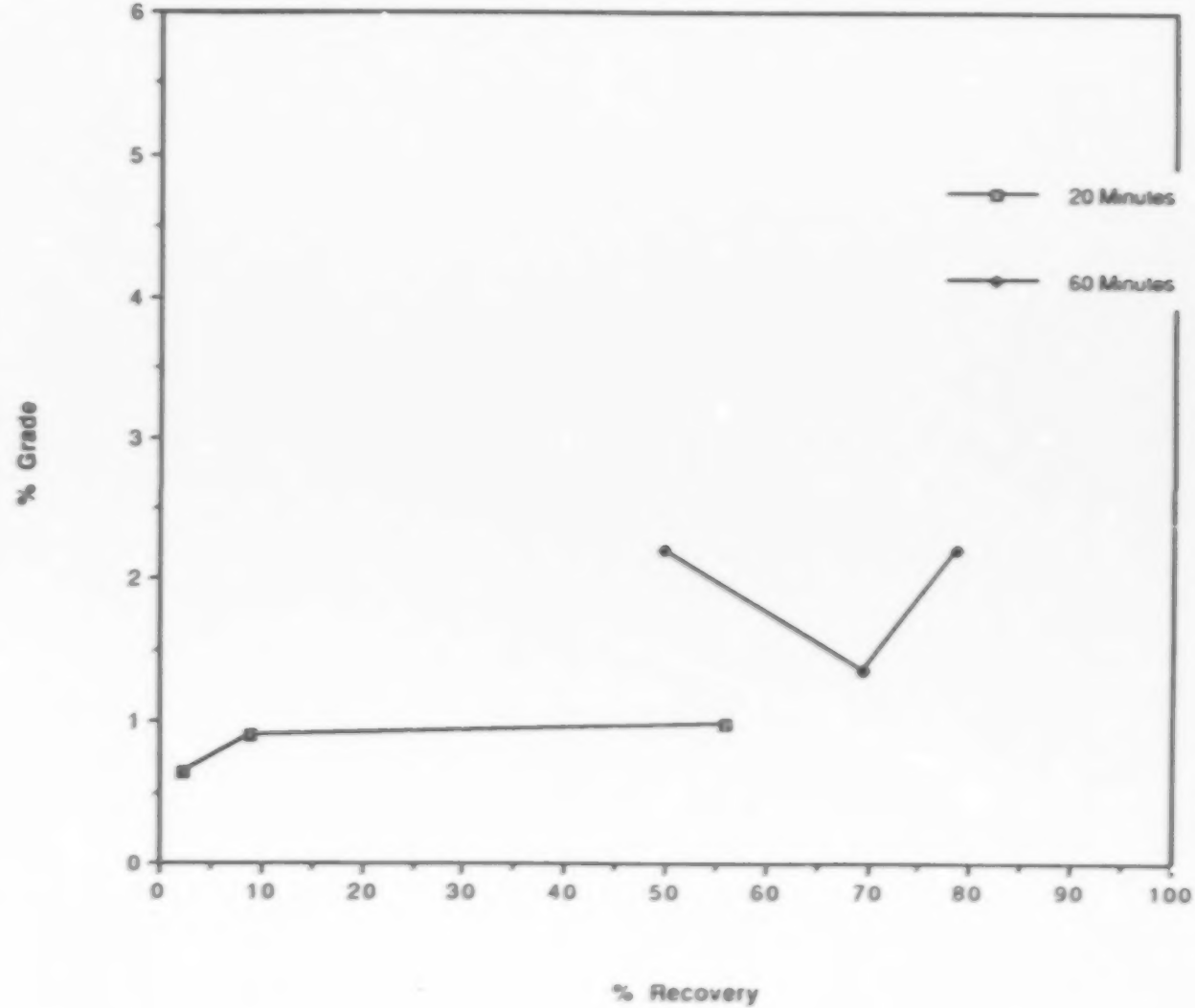


Figure 27

Effect of Time of Bioconditioning on

Pentlandite Vs. Pyrrhotite Recovery

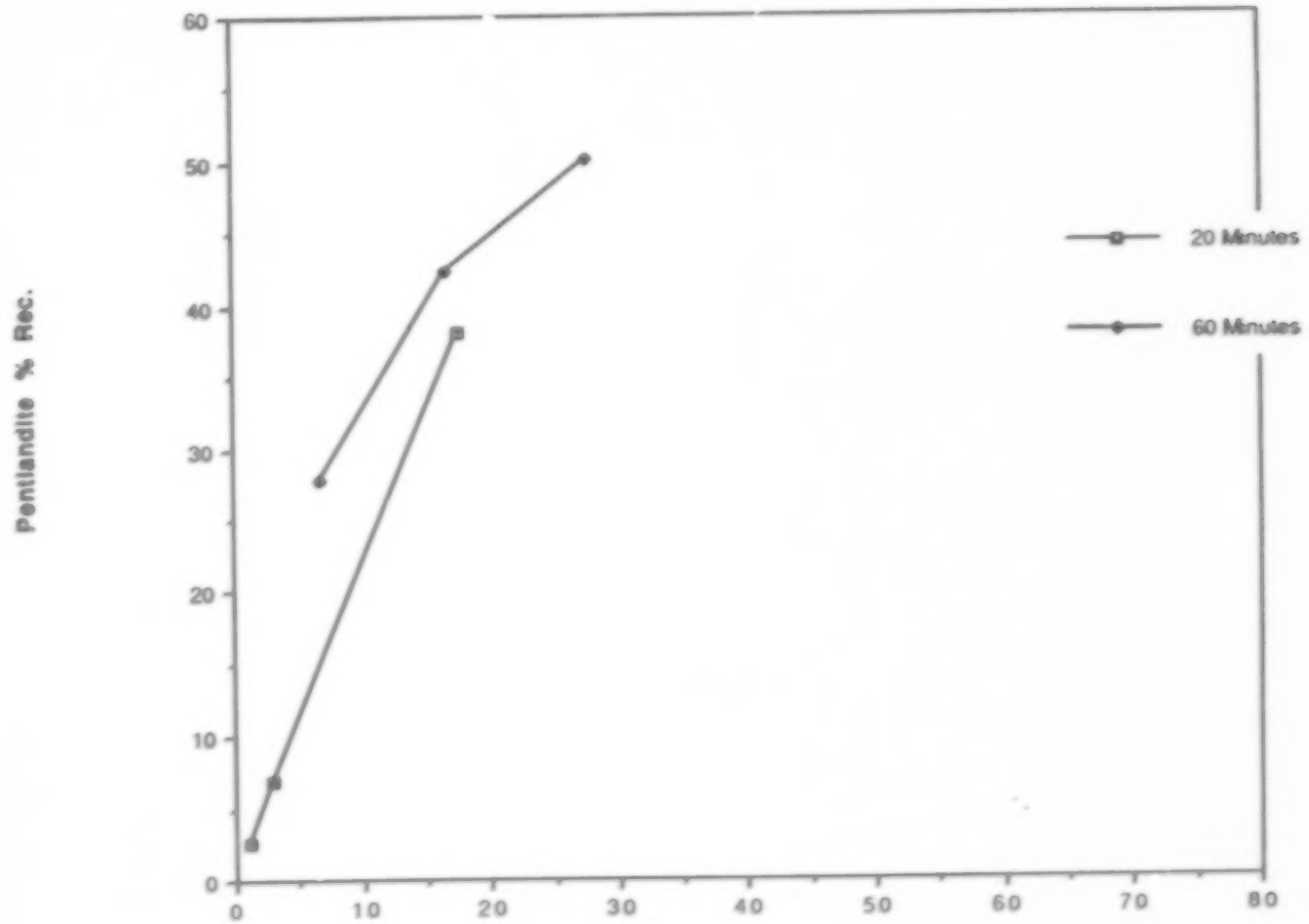


Figure 28

Effect of pH of Bioconditioning on

Ni Flotation Products

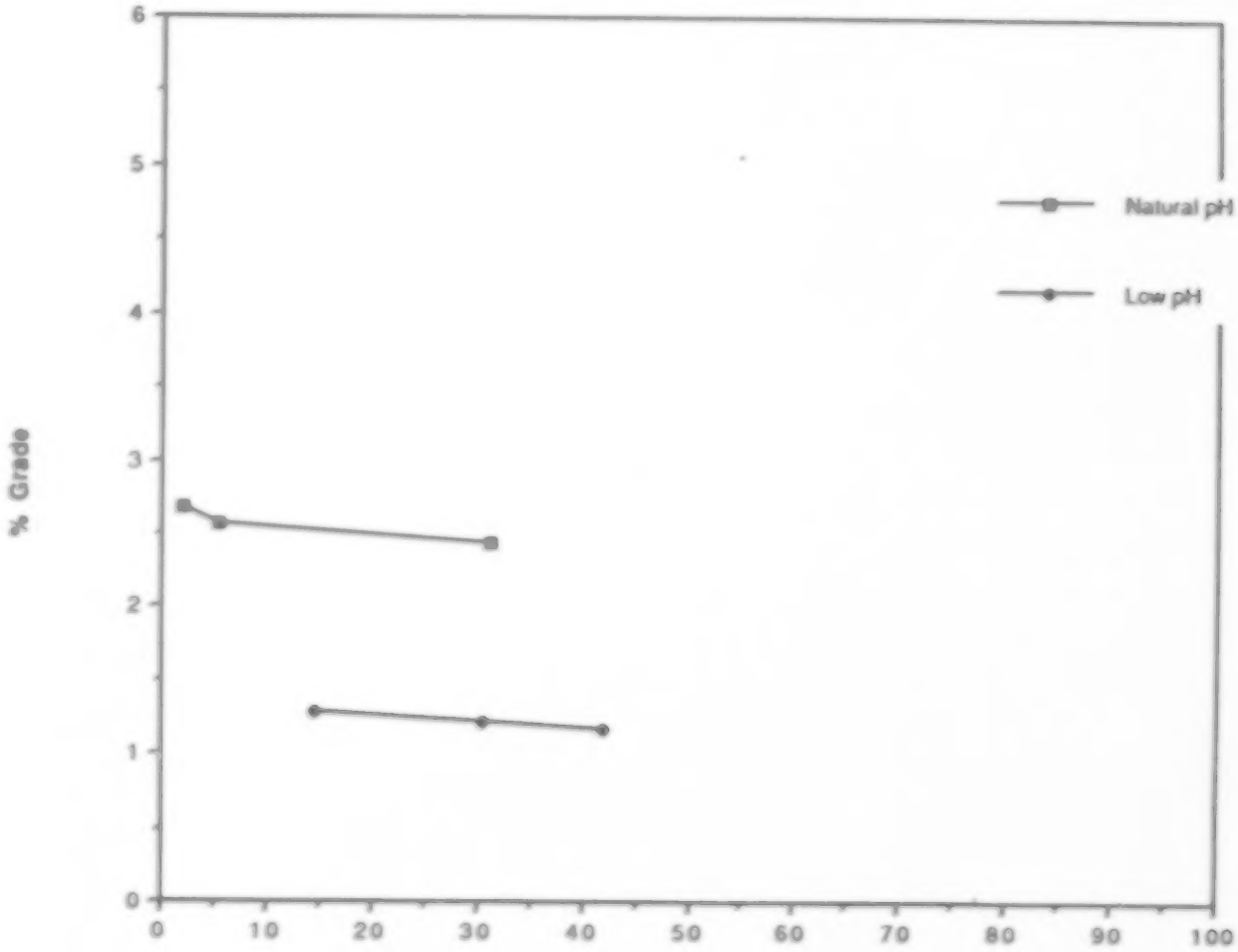


Figure 29

Effect of pH of Bioconditioning on

Cu Flotation Products

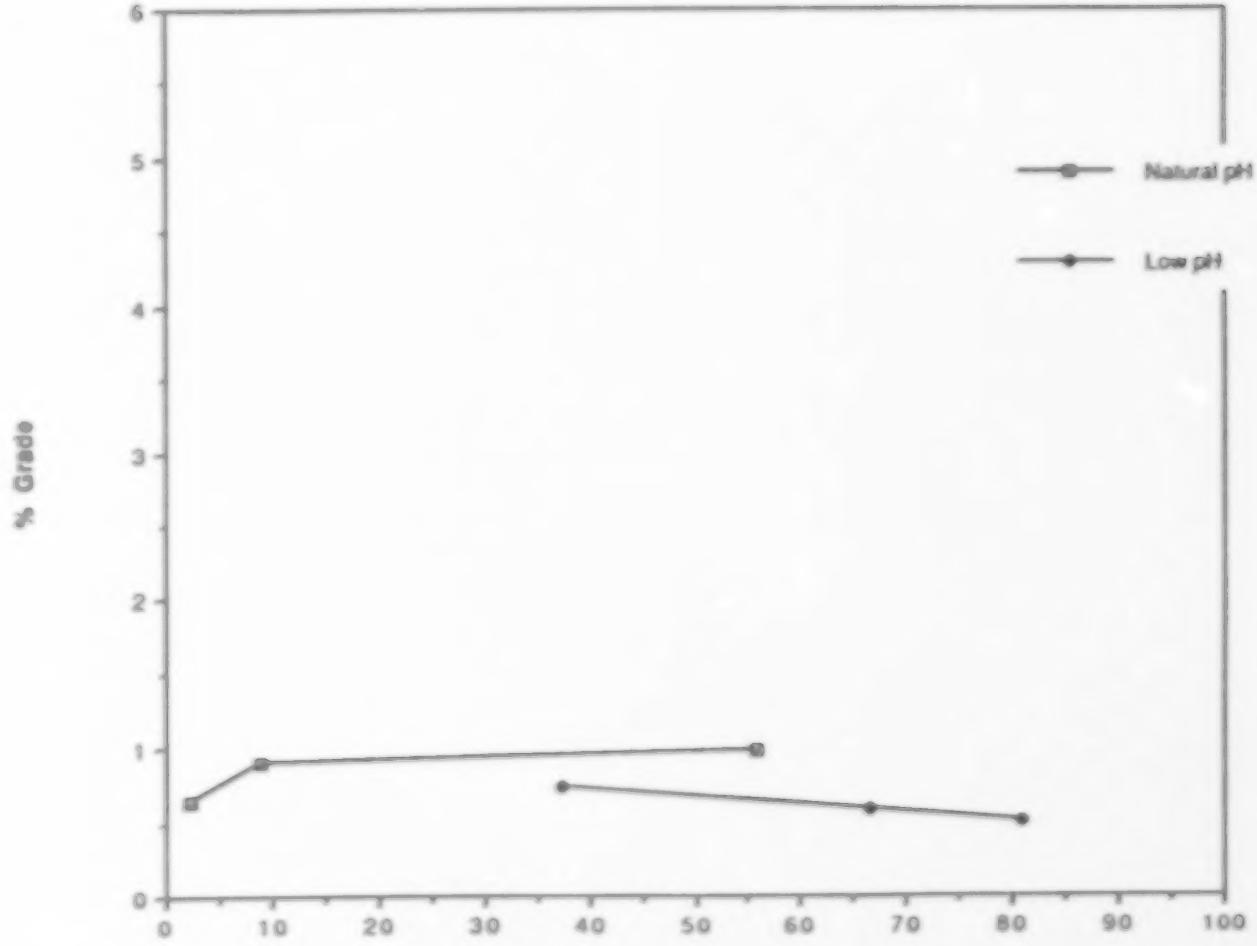


Figure 30

Effect of pH of Bioconditioning on
Pentlandite Vs. Pyrrhotite Recovery

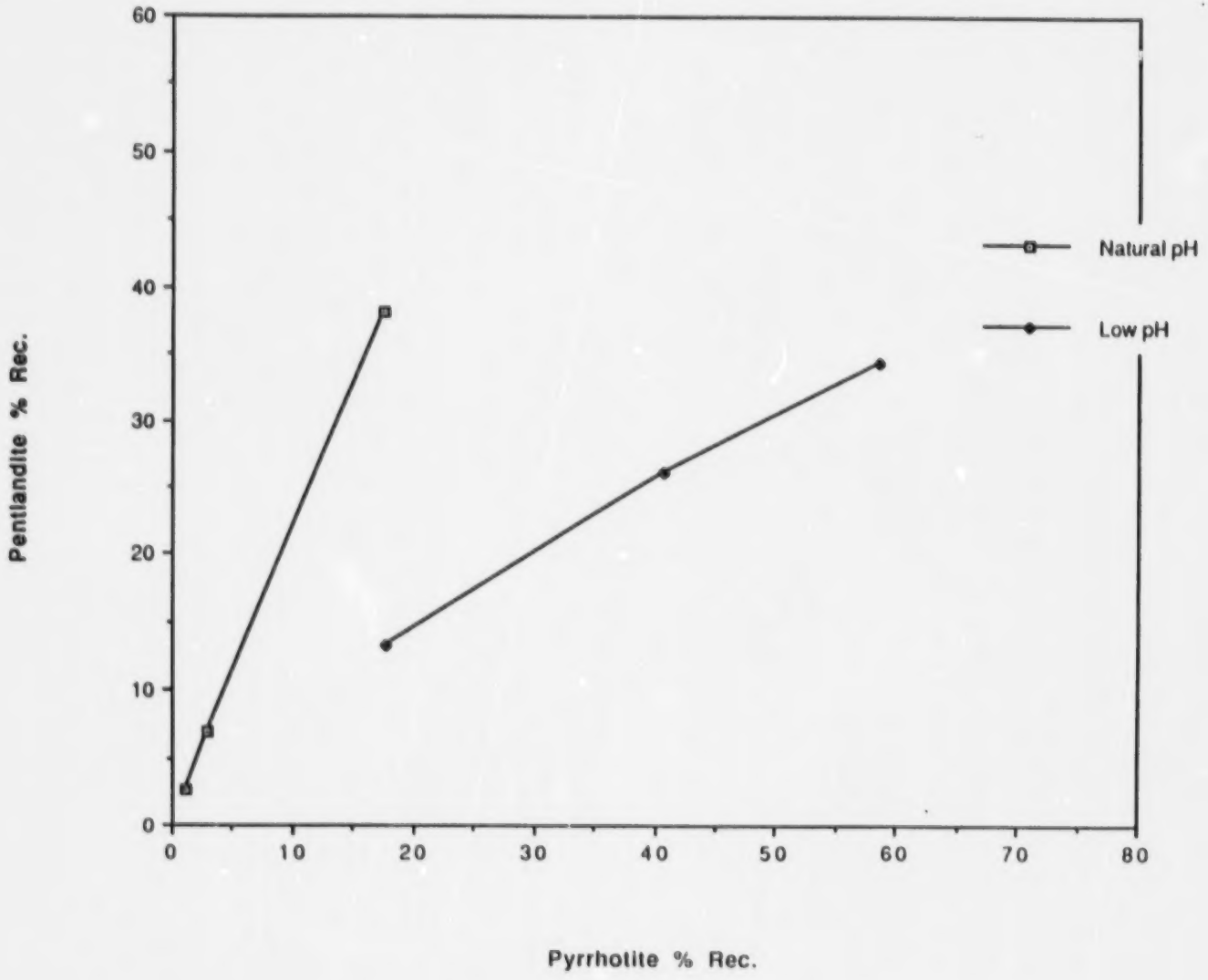


Figure 31

Effect of 120 Min. Bioconditioning on Ni Flotation Products

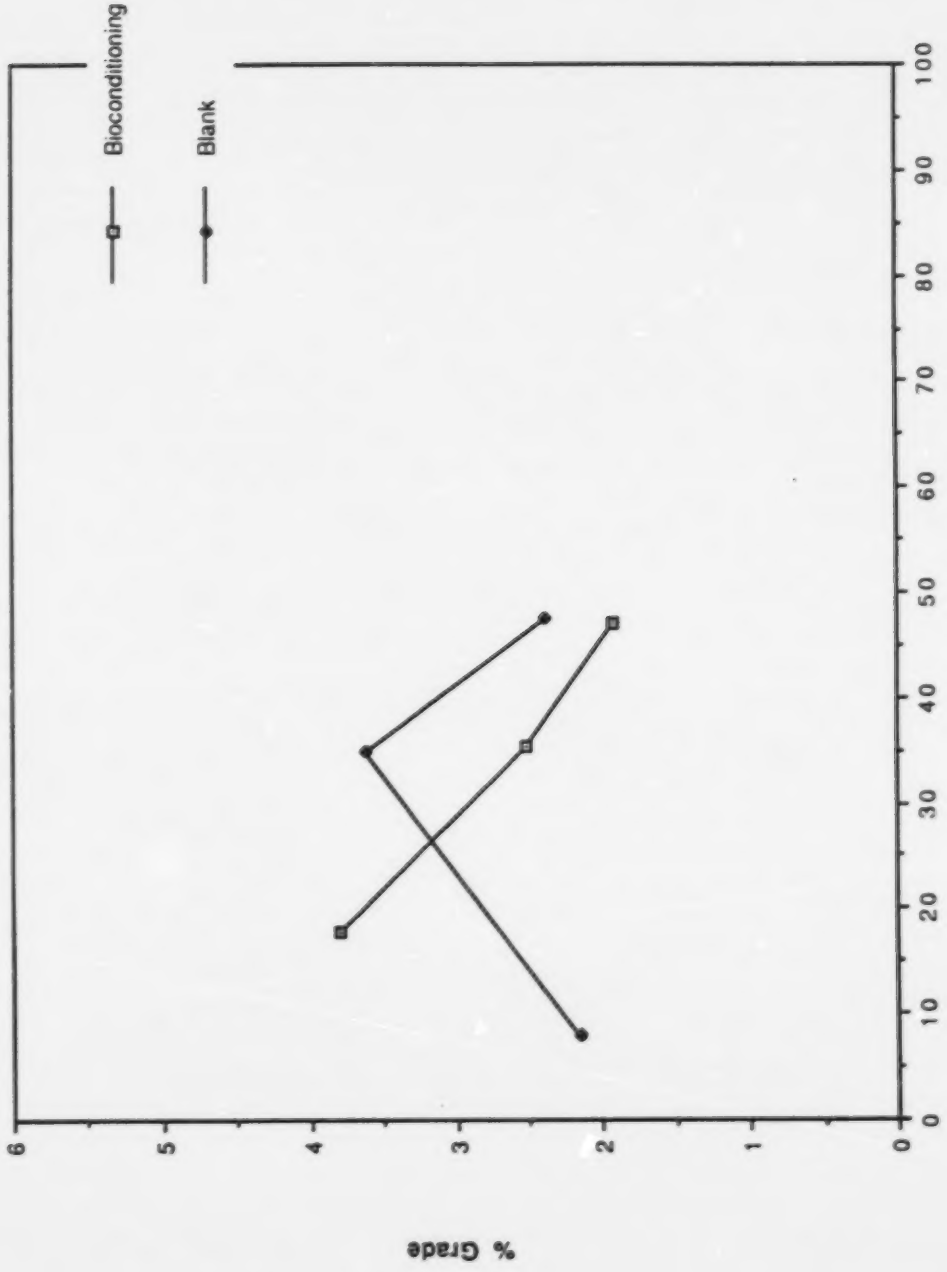


Figure 32

Effect of 120 Min. Bioconditioning on

Cu Flotation Products

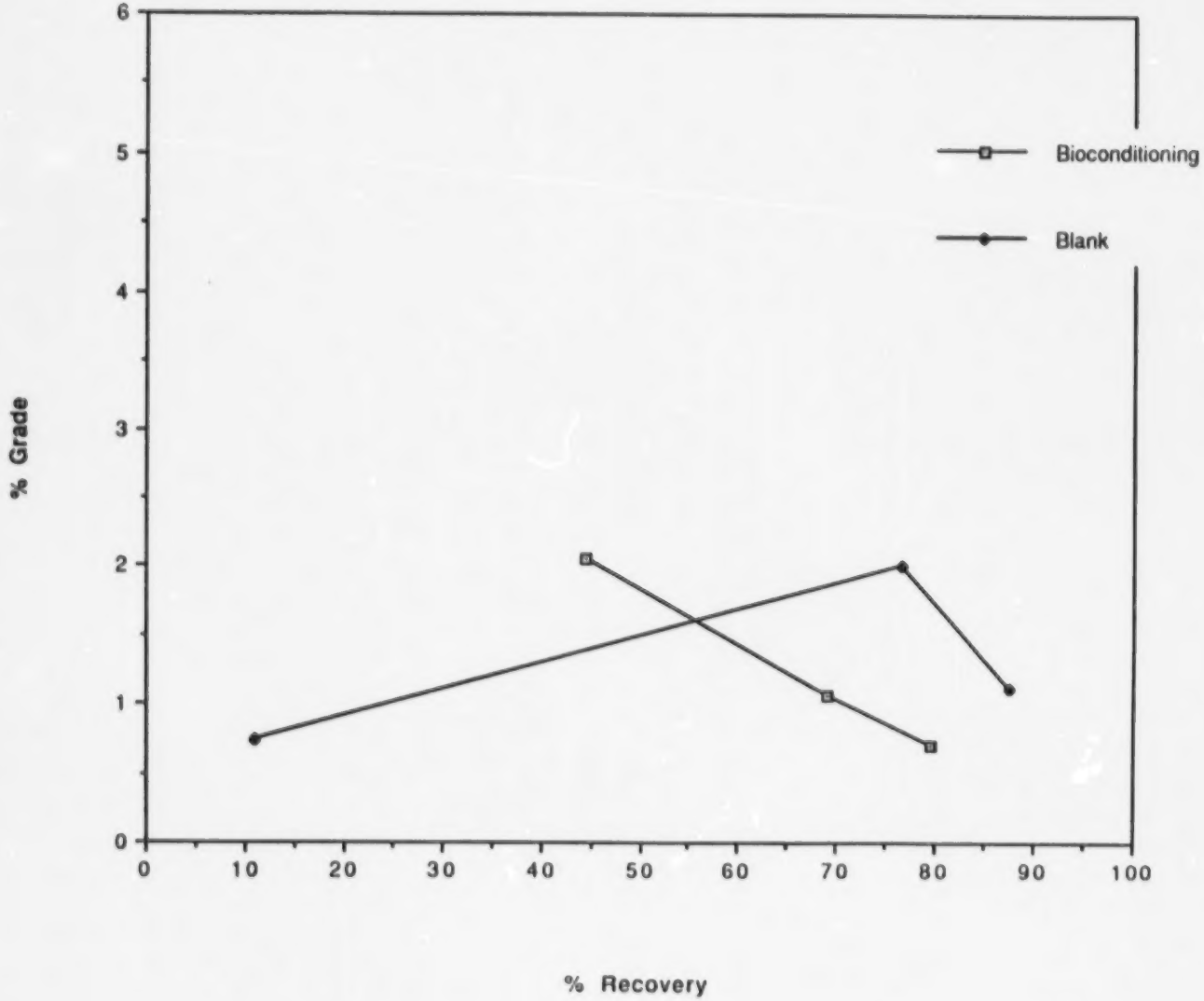


Figure 33

Effect of 120 Min. Bioconditioning on

Pentlandite Vs. Pyrrhotite Recovery

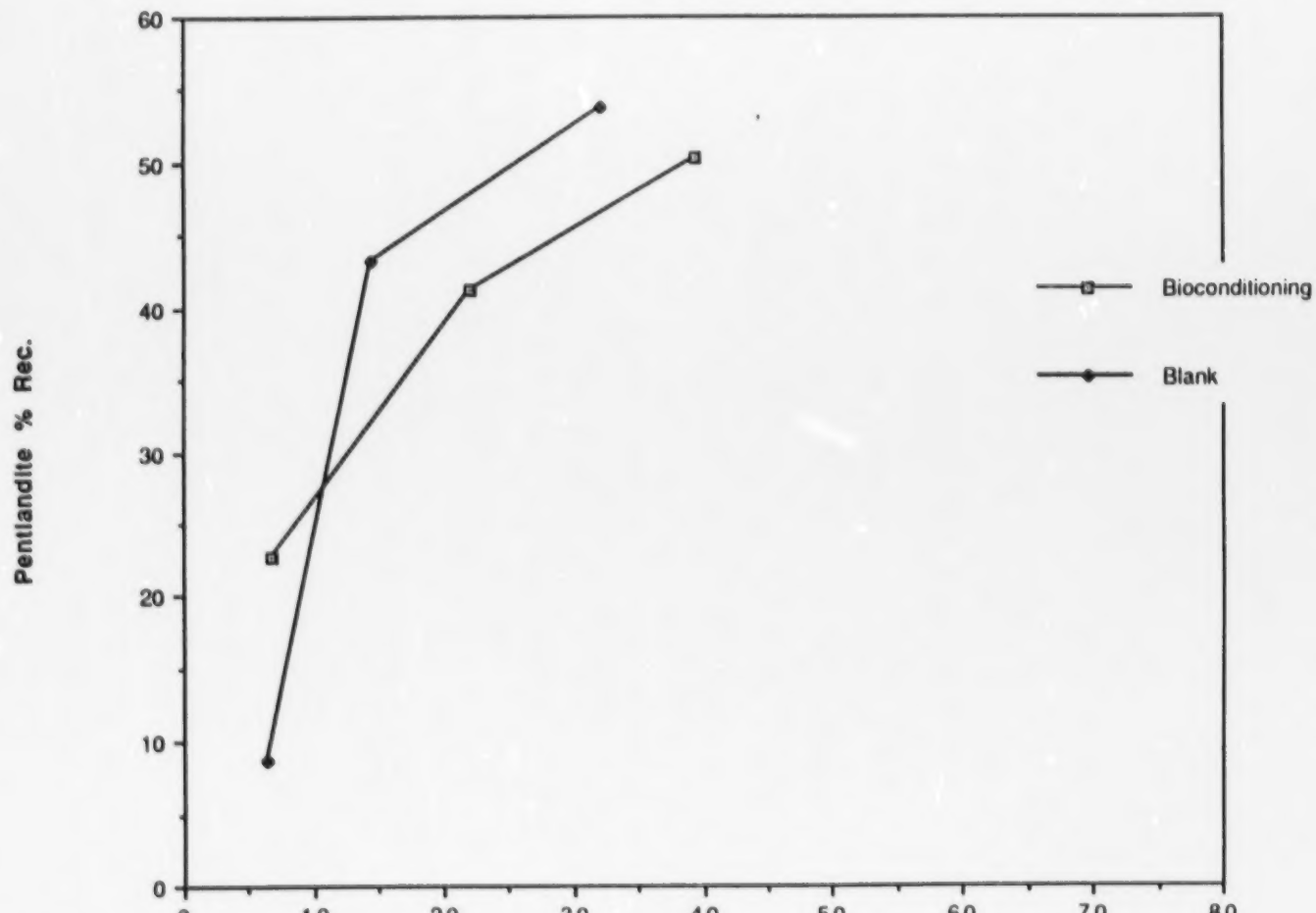


Figure 34

Effect of Frother Dose on Bioconditioned

Ni Flotation Products

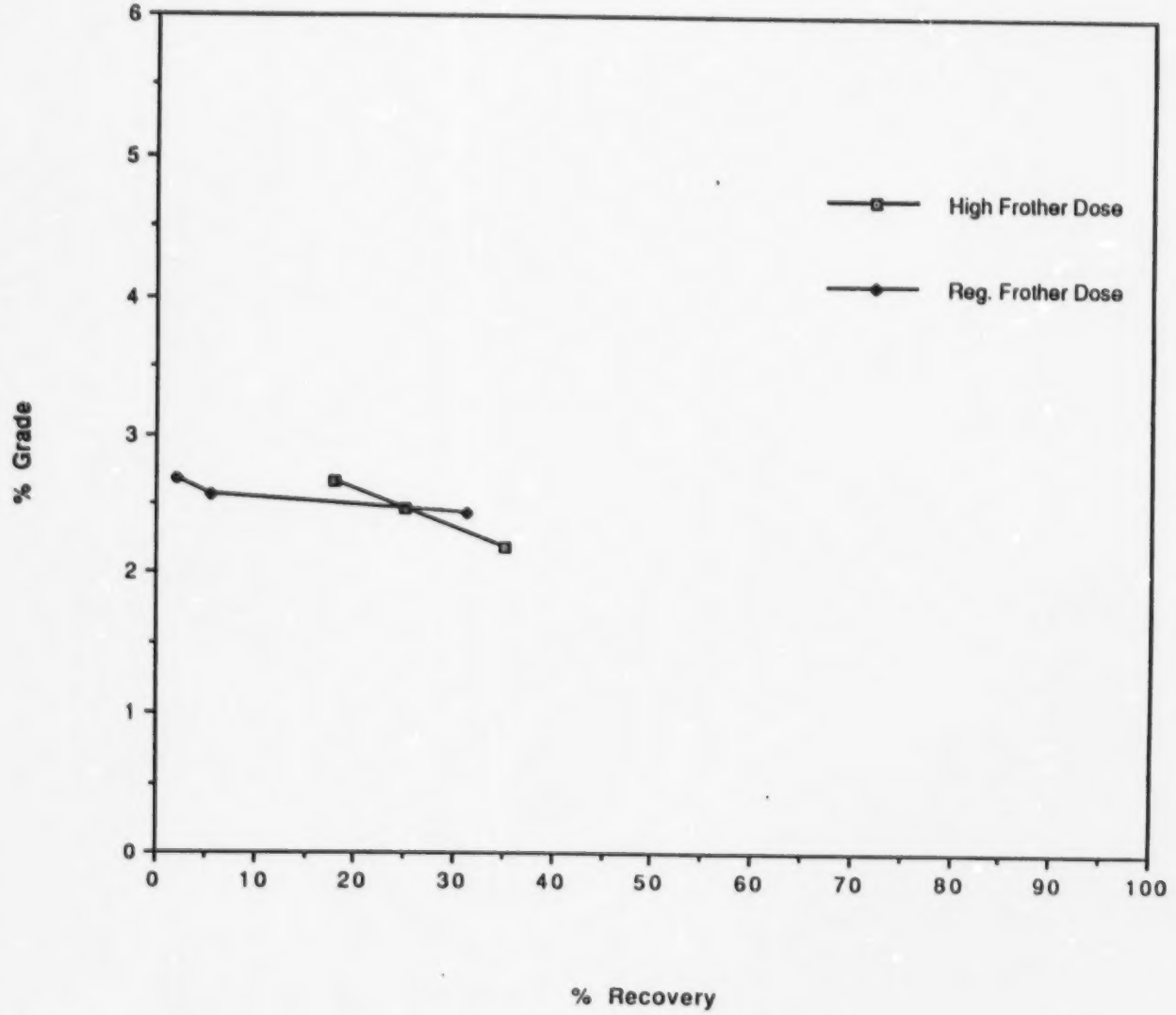


Figure 35

Effect of Frother Dose on Bioconditioned

Cu Flotation Products

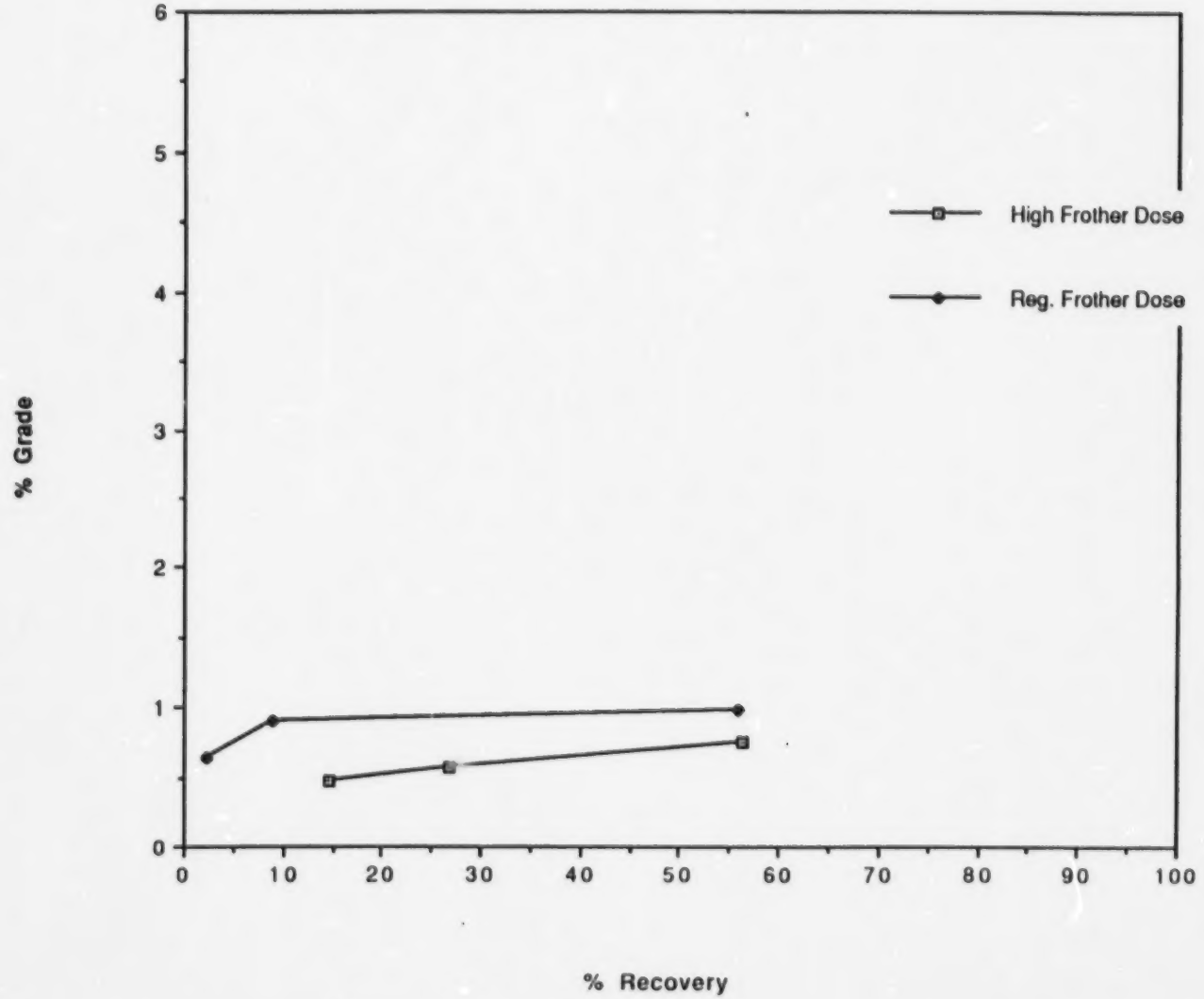
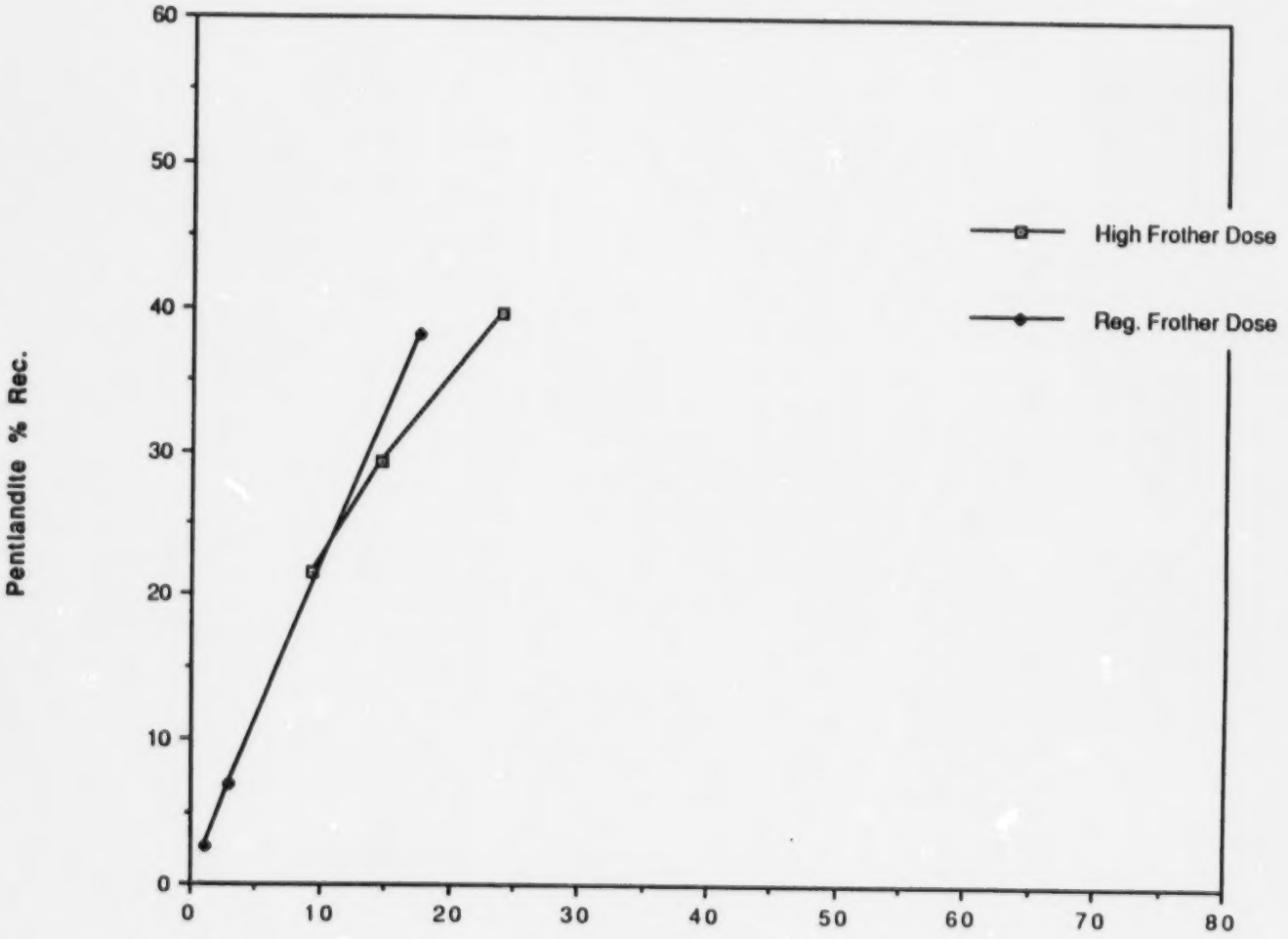


Figure 36

Effect of Frother Dose on Bioconditioned on

Pentlandite Vs. Pyrrhotite Recovery



APPENDIX III: Cost Analysis

COST ANALYSIS

DSS Project # 15SQ 23440-4-9157

Month/Year	DSS Cost ($)	Falconbridge in-kind support ($)	Total ($)
September 1990	4,825.10	1,400.00	6,225.10
October 1990	10,699.78	800.00	11,439.78
November 1990	9,430.58	1,600.00	11,030.58
December 1990	7,297.31	500.00	7,797.31
January 1991	5,819.81	3,195.00	9,014.81
February 1991	4,492.69	3,050.00	7,542.69
March 1991	2,925.73	4,285.00	7,210.73
TOTAL	$45,431.00	$14,830.00	$60,261.00

The original proposed total cost was to have been $64,531.00, composed of $45,431.00 Crown share, $19,100.00, Falconbride share. Due to the nature of the project having an unspecified volume of analytical testwork, the final Falconbridge share was 44,270.00 short of the original amount proposed.

Supply and Services Canada / Approvisionnements et Services Canada

DSS MAS 9143 3 (4/81)

CONTRACT PLAN AND REPORT FORM – FORMULE DE PROJET DE CONTRAT ET DE RAPPORT

CONTRACT TITLE – TITRE DU CONTRAT

CONTRACTOR – ENTREPRENEUR

File No. – N° du dossier: 15SQ-23440-0-9157

Serial No. – N° de série:

Task description – Description de la tâche	Task duration in months – Durée de la tâche en mois												Task cost – Coût de la tâche		
	1 Sept	2 Oct	3 Nov	4 Dec	5 Jan	6 Feb	7 March	8	9	10	11	12	Planned cost – Coût prévu	Actual cost – Coût réel	Date
MICRO-ORGANISM ISOLATION													$18.1K	$20,648.88	Dec 15/11
LEACH and BIOTECH TESTWORK													$30.6K	$27342.70	Feb 28/11
PROCESS TESTWORK (VAT LEACH)													$ 9.8K	$10,000.00	March 15/11
FEASIBILITY REPORT													$ 6.6K	$2253.42	March 31/91
Planned cost by month – Coût prévu pour chaque mois	$6,000	$6,000	$13,750	$7,650	$12,550	$15,850	$3,300						Plan $65,100		
Act. Forecast. DSS – E.T.C. by month – Prévision pour ch. mois	$4825.10	10,639.78	9,430.58	7,297.31	$5819.81	4,492.69	2925.73							Actual – Coûts réels $60,261.00	Date Mar 31/11
Act. Forecast. FBG – E.T.C. by month – Prévision pour ch. mois	$1400.00	800.00	1,600.00	500.00	3195.00	3,050.00	4285.00								
TOTAL	$6225.10	11,137.78	11,030.58	7797.31	9014.81	7,542.69*	7210.73						DSS $45481.00		
													FBG $14830.00		
													TOTAL $60,261.00		

* Includes in-kind Falconbridge financial support.

FALCONBRIDGE LIMITED

Inter-Office Memorandum

Date : Oct. 15, 1990

Project code: 80-411

To : M.Collins, J.Fyfe & P.Tackaberry (ORTECH)

cc : R.E.Michelutti, B.A.Mikkila, S.O.Fekete, D.A.Neudorf, M.R.Austreng, G.Springer & E.G.Desforges

From : G.W.Heinrich

Subject: In-Kind Falconbridge Support for DBS (Contract # 158Q.23440-4-9157) During Sept. 1990

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For the month of Sept. 1990, ORTECH received the following in-kind support from Falconbridge Limited:

* Consulting man-hours *):	meetings	12 hrs
	field trips	2 hrs
		14 hrs
* Chemical analyses:	none	
* Mineralogical analyses:	none	
Total		$ 1,400

*) Preliminary estimate $ 100 per man-hour worked, SI Cost Analysis Sheet for 80-411 for Sept. 1990 not available

The activities during Sept. 1990 were aimed at clarifying the project scope and to help ORTECH to obtain suitable sample material:

* A meeting was held on Sept.24 at MTC/Falconbridge to discuss Falconbridges' in-kind support as well as the structure and scope of the project (Attendees: DAN, EHC, MC, REM, MRA, BAM, JDF, GWH & P.Tackaberry/ORTECH) and

* a samples were taken from several locations at the East-End properties at the same day (P.Tackaberry & BAM).

G.W.Heinrich

FALCONBRIDGE LIMITED **Inter Office Memorandum**

File: 80-411

Date: November 8, 1990

To: M. Collins, J. Fyfe, P. Tackaberry (ORTECH)

cc: R.E. Michelutti, B.A. Mikkila, S.O. Fekete, D.A. Neudorf, M.R. Austreng, G. Springer, E.G. Desforges

From: G.W. Heinrich

Subject: **IN-KIND FALCONBRIDGE SUPPORT FOR DSS (CONTRACT #15SQ.23440-4-9157) DURING OCTOBER, 1990**

For the month of October, 1990, ORTECH received the following in-kind support from Falconbridge Limited:

• Consulting man-hours:	field trips	8 hrs
	other	-
		8 hrs
• Chemical analyses:	none	
• Mineralogical analyses:	none	____
	TOTAL	$ 800

The activities during October, 1990, consisted of sampling of various process streams of Strathcona Mill and of several disposal sites in the Onaping area to obtain suitable materials for further study.

G.W. Heinrich

FALCONBRIDGE LIMITED

Inter Office Memorandum

File: 80-411

Date: December 3, 1990

To: M. Collins, J. Fyfe, P. Tackaberry (ORTECH)

cc: R.E. Michelutti, B.A. Mikkila, S.O. Fekete, D.A. Neudorf, M.R. Austreng, G. Springer, E.G. Desforges

From: G.W. Heinrich

Subject: **IN-KIND FALCONBRIDGE SUPPORT FOR DSS (CONTRACT #15SQ.23440-4-9157) DURING NOVEMBER 1990**

For the month of November 1990, ORTECH received the following in-kind support from Falconbridge Limitad:

* Consulting man-hours:	field trips	-
	other	12 hrs
		12 hrs
* Chemical analyses:		$ 600
* Mineralogical analyses:		none
	Total	$ 1,800

The activities during November 1990 consisted of preparing and assaying seven solid and six liquid samples from scoping testwork at ORTECH. In addition to chemical assays for Ni, Cu, S and Fe, the pH values of the solutions received, as well as the solids' densities were measured. The results obtained are shown in the Table attached.

Gustav Heinrich

G.W. Heinrich

FALCONBRIDGE LIMITED

Inter Office Memorandum

File: 80-411

Date: January 14, 1990

To: M. Collins, J. Fyfe, P. Tackaberry (ORTECH)

cc: R.E. Michelutti, B.A. Mikkila, S.O. Fekete/80-411, D.A. Neudorf, M.R. Austreng, G. Springer, E.G. Desforges

From: G.W. Heinrich

Subject: IN-KIND FALCONBRIDGE SUPPORT FOR DSS DECEMBER (CONTRACT #15SQ.23440-4-9157) DURING ~~NOVEMBER~~ 1990

For the month of December 1990, ORTECH received the following in-kind support from Falconbridge Limited:

• Consulting Man-Hours	field trips		-
	other		5 hrs
			5 hrs
• Chemical Analyses		$	-
• Mineralogical Analyses			none
TOTAL		**$**	**500**

The activities during November 1990, consisted of reviewing the work completed to date, and the discussion of the possible options during a steering committee meeting on December 12, 1990 at MTC/Falconbridge.

G. Heinrich

G.W. Heinrich

FALCONBRIDGE LIMITED

Inter-Office Memorandum

Project code: 80-411

Date: Feb. 08, 1991

To: M. Collins, J. Fyfe, P. Tackaberry (ORTECH)

cc: R.E. Michelutti, B.A. Mikkila, S.O. Fekete, D.A. Neudorf, M.R. Austreng, G. Springer, E.G. Desforges

From: G.W. Heinrich

Subject: IN-KIND FALCONBRIDGE SUPPORT FOR DSS (CONTRACT #15SQ.23440-4-9157) DURING JAN. 1991

For the month of January, 1991, ORTECH received the following in-kind support from Falconbridge Limited:

• Consulting man-hours:	field trips	--
	other	6 hrs
		6 hrs
• Chemical analyses:		$ 2,595
• Mineralogical analyses:		none
	Total	$ 3,195

The activities during November, 1990 consisted of preparing and assaying 2 solid and 83 liquid samples from microbial adaption testwork at ORTECH. Early indications are that adapting the Thiobacilly isolated to Strathcona tailings was successful. More detailed results on this will be communicated in ORTECH's progress report for Jan. 1991. The current work at ORTECH will focus on enhancing microbial activities towards practical applications.

G.W.Heinrich

FALCONBRIDGE LIMITED

Inter-Office Memorandum

Project code: 80-411

Date: Mar.05, 1991

To: M. Collins, J. Fyfe, P. Tackaberry (ORTECH)

cc: R.E. Michelutti, B.A. Mikkila, S.O. Fekete, D.A. Neudorf, M.R. Austreng, G. Springer, E.G. Desforges

From: G.W. Heinrich

Subject: **IN-KIND FALCONBRIDGE SUPPORT FOR DSS (Contract #15SQ.23440-4-9157) DURING FEBRUARY, 1991.**

For the month of February, 1991, ORTECH received the following in-kind support from Falconbridge Limited:

• Consulting man-hours:	field trips	–
	other	11 hrs
		11 hrs
• Chemical analyses:		$1,950
• Mineralogical analyses:		none
Total		$3,050

The activities during February, 1991 consisted of preparing and assaying 65 liquid samples from testwork at ORTECH on accelereated bioleaching kinetics. Detailed results on this will be communicated in ORTECH's progress report for Feb.1991. The current work at ORTECH will comprise exploratory tests on depressing pyrrhotite by applying microorganisms prior to sulphide flotation. Scoping tests on 'biocapping' of tailings or metal sorption from tailings effluents are currently not conducted because of patent rights or overlap with other DSS contracts.

G. Heinrich

G.W.Heinrich

FALCONBRIDGE LIMITED Inter Office Memorandum

File: 80-411

Date: April 5, 1991

To: P.F. Wells, M. Collins, J. Fyfe, T. Tackaberry (ORTECH)

cc: R.E. Michelutti, B.A. Mikkila, S.O. Fekete/File, D.A. Neudorf, M.R. Austreng, G. Springer, E.G. Desforges

From: G.W. Heinrich

Subject: **IN-KIND FALCONBRIDGE SUPPORT FOR DSS (CONTRACT #15SQ.23440-4-9157) DURING MARCH 1991**

For the month of March 1991, ORTECH received the following in-kind support from Falconbridge Limited:

* Consulting man-hours	field trips	-
	other	7 hrs
		7 hrs
* Chemical analyses		$3,585
* Mineralogical analyses		none
Total		**$4,285**

The activities during March 1991 consisted of preparing and assaying 71 liquid samples and 33 solid samples from testwork at ORTECH. One part of the testwork was aimed at accelerated bioleaching kinetics. The possibility of enhancing the separation of pentlandite and pyrrhotite by a bioconditioning step followed by flotation was studied in a second part of the testseries. In some of the final leach liquors, the nickel concentration exceeded 500 ppm. Adding copper ions as a catalyst seems to lead to lower pH values without enhancing the bioleaching kinetics of nickel. According to this, it might help to reduce acid run-off by disposing off the pyrrhotite tailings separate from tailings of higher chalcopyrite content. The bioconditioning was conducted with additions of highly concentrated thiobacilli in order to come to a selective surface alteration of pyrrhotite. Reverse flotation of pentlandite was observed for bioconditioning at lower pH values. Detailed results on this will be communicated in ORTECH's progress report for March 1991. A steering committee meeting to review the outcome of ORTECH's study is planned for April 18th, 1991.

G.W. Heinrich